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Key Points:

- Record of large volcanic eruptions in the Holocene is constructed from chemical analysis of a 3,400-m ice Core from WAIS Divide, Antarctica
- Atmospheric aerosol mass loading of climate-impacting sulfur is dominated by explosive eruptions with extraordinarily high sulfur emission
- No apparent trend is found in number of volcanic eruptions per millennium; frequency in the most recent millennium is not particularly high

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Comprehensive Record of Volcanic Eruptions in the Holocene (11,000 years) From the WAIS Divide, Antarctica Ice Core

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Abstract A comprehensive record (WHV2020) of explosive volcanic eruptions in the last 11,000 years is reconstructed from the West Antarctica Ice Sheet Divide deep ice core (WDC). The chronological list of 426 large volcanic eruptions in the Southern Hemisphere and the low latitudes during the Holocene are of the highest quality of all volcanic records from ice cores, owing to the high-resolution chemical measurement of the ice core and the exceptionally accurate WDC timescale. No apparent trend is found in the frequency (number of eruptions per millennium) of volcanic eruptions, and the number of eruptions in the most recent millennium (1,000–2,000 CE) is only slightly higher than the average in the last 11 millennia. The atmospheric aerosol mass loading of climate-impacting sulfur, estimated from measured volcanic sulfate deposition, is dominated by explosive eruptions with extraordinarily high sulfur mass loading. Signals of three major volcanic eruptions are detected in the second half of the 17th century (1700–1600) BCE when the Thera volcano in the eastern Mediterranean was suspected to have erupted; the fact that these signals are synchronous with three volcanic eruptions detected in Greenland ice cores suggests that these are likely eruptions in the low latitudes and none should be attributed exclusively to Thera. A number of eruptions with very high sulfur mass loading took place shortly before and during an early Holocene climatic episode, the so-called 8.2 ka event, and are speculated to have contributed to the initiation and magnitude of the cold event.

Plain Language Summary A complete record of large volcanic eruptions during the last 11,000 years has been produced from a detailed chemical analysis of a 3,400-m long ice core from Antarctica. The record is a chronological list of 426 explosive volcanic eruptions with the quantity of emitted volcanic materials that can impact the global climate. A number of very large eruptions some 8,200 years ago may have triggered and/or enhanced an abrupt cold episode in Earth's climate history. This record does not provide conclusive evidence that the Thera eruption occurred in the 17th century BCE.

1. Introduction

Volcanic eruptions emit large amounts of sulfur, mainly as SO_2, into the atmosphere, where the sulfur is oxidized to sulfuric acid, forming sulfate aerosols. The aerosol particles impact the energy budget of Earth's surface by scattering incoming solar radiation. Consequently, volcanism plays an important role in climate variation (Cole-Dai, 2010; Robock, 2000). Recent research has focused on understanding the quantitative relationship between the timing and magnitude of eruptions and the climatic impact (Bethke et al., 2017; Cooper et al., 2018; Timmreck et al., 2016). One critically important approach is to examine the volcanic impact in paleoclimate records. This approach requires and benefits from high-quality records of past volcanic eruptions (Cole-Dai, 2010).

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Volcanic sulfate aerosols as well as fine ash (tephra) deposit with snow and are preserved in polar ice sheets and glaciers. The signals of past volcanic eruptions can be detected and quantified with measurement of acidity, sulfate, or elemental sulfur in polar ice cores (Hammer, 1977). Volcanic records from polar ice cores are lengthy, comprehensive, and of high resolution and, therefore, considered the most valuable. Additionally, they are highly valued in examining the volcano-climate relationship, because volcanic forcing can be quantitatively estimated with ice core chemical measurement without the feedback effect of a climate response (tree-ring volcanic records are dependent on temperature effect on growth). Furthermore, climatic and volcanic records derived from the same ice core minimize the influence of chronological errors or dating uncertainties (Cole-Dai, 2010).

Although numerous volcanic records have been obtained from Antarctica and Greenland ice cores, the quality of the records varies significantly, as a result of variations in the characteristics of the ice cores, and in the type and quality of the chemical measurement (Gao et al., 2008; Sigl et al., 2015). In general, ice cores from locations of high snow accumulation can be analyzed with high resolution, leading to highly resolved volcanic records with reliable chronology. However, the time coverage by these cores of certain depths may be limited. On the other hand, cores from locations of low snow accumulation can provide long (10^3–10^5 years) records (e.g., Castellano et al., 2004). The limited dating accuracy and precision of the cores from low accumulation locations usually leads to large uncertainties in the timing of eruptions and their associated climate response, thereby making it difficult to assess the true volcanic impact on climate.

A 3,405-m ice core was drilled during 2007–2012 at the West Antarctica Ice Sheet Divide (WAIS Divide) location in central West Antarctica. The WAIS Divide ice core (WDC) provides highly resolved, accurately and precisely dated records of climate variations in the last 68,000 years (Buizert, Adrian, et al., 2015; Sigl et al., 2016). Among the numerous physical and chemical measurements of WDC are concentrations of elemental sulfur, sulfate, and other trace chemical impurities, which can be used to construct long and highly detailed records of explosive volcanic eruptions. For example, Sigl et al. (2013, 2015) investigated the climate variation resulting from volcanic forcing in the past two millennia using detailed volcanic records from WDC and other ice cores. Here, we present the volcanic record of the last 11,000 years (the Holocene) from chemical analysis of the upper part (1,911 m) of WDC. Our main objectives are (1) to reconstruct a comprehensive and detailed record of explosive volcanic eruptions in the Holocene and (2) to assess the quality of this new record by comparison with published records from both ice cores and other compilations when the records overlap. We highlight two cases of historically or climatically significant eruptions in the Holocene. Highlighting these cases is not intended as a thorough study of the eruptions and their impact; rather, the intention is to illustrate the potential utility of this high-quality volcanic record.

The magnitude of ice core signals of a volcanic eruption can vary significantly among ice cores, due to variations in atmospheric transport of volcanic aerosols, in scavenging efficiency during snow deposition, in preservation of the signal in the snow strata, and in signal detection and quantitation. Consequently, reconstruction of volcanic forcing on climate and systematic investigation of the climate impact of volcanism ought not rely on record from a single ice core. Composited records from multiple ice cores are usually used for such reconstruction and investigation (Gao et al., 2008; Sigl et al., 2014).

2. Methods and Ice Core Data

2.1. Ice Core and Analysis

WAIS Divide (79°28′ S, 112°05′ W; 1,766 m above sea level) was selected as the site for a deep West Antarctica ice core with potential for long climate records of high temporal resolution, both because of its location near the main West Antarctica Ice Sheet divide and because of the high snow accumulation rate, averaging 0.22 m of ice equivalent snowfall per year (Banta et al., 2008). The top 577 m and the ice below 1,300 m of the main ice core, WDC and previously designated as WDC06A, were analyzed for a suite of elements, including sulfur and sodium, with a continuous melting device interfaced with inductively coupled plasma mass spectrometers (ICP-MS). The section between 577 and 1,300 m (brittle ice) was sampled both manually and with continuous melting; samples were analyzed with ion chromatography (IC) for major ions including sulfate and sodium ion. A detailed description of the chemical measurements can be found in Sigl et al. (2016) and Cole-Dai et al. (2013). The reliability of the chemical analyses and the quality of the sulfur and sulfate data have been discussed previously (Cole-Dai et al., 2013; Sigl et al., 2016).

2.2. Ice Core Dating

The WDC core is dated with the technique of annual layer counting (Sigl et al., 2016) and synchronization with previously established ice core chronologies (Buizert, Cuffey, et al., 2015). Dating of the Holocene portion (0 to ~1,900 m), which is defined as the time period of up to 11,000 years before present (present = 1950 CE) or 0–11 ka BP, of WDC relied on annual oscillations in concentrations of aerosol species determined with high-resolution chemical measurement (Sigl et al., 2016). Briefly, the annual oscillations in multiple chemical species were counted beginning at the top of the ice core to establish the depth of each annual layer. The accuracy of the age determination was confirmed with tree-ring chronologies by matching prominent events in ^{10}Be (ice cores) and ^{14}C (tree rings). The uncertainty of age determination is generally less than 0.3% of the age (approximately 30 years at 11,000 years BP) and the maximum uncertainty is 0.5% (Sigl et al., 2016). Dating uncertainty results from rare occasions of poor preservation of the annual snow layer and/or ambiguous identification of annual layer markers.

Ice sheets are subject to vertical and horizontal strain as snow accumulates and ice flows, leading to thinning of deep layers relative to their original thickness (in ice or water equivalent) at the time of snow deposition. Since the annual flux of a chemical species depends on the accumulation rate (thickness of the annual layer) at the time of deposition, measured annual layer thickness in the core must be corrected for glacial thinning to reconstruct the original accumulation rate. A modified Dansgaard-Johnsen (1969) model was used by Cuffey et al. (2016) to calculate the thinning correction factor, measured layer thickness as a fraction of the original layer thickness, as a function of depth in WDC. The calculated thinning correction factor ranges from 1.00 at the top of the core (no thinning) to 0.476 at 1,911 m depth and the resulting accumulation rate history is presented in Fudge et al. (2016).

2.3. Sulfur/Sulfate Data

Sulfate in sea salt aerosols contributes to sulfur/sulfate (sulfur or sulfate) in Antarctic snow. The sea salt contribution in WAIS Divide snow can be computed from the measured total sulfur or sulfate concentration and the sodium concentration in a sample and the sulfur or sulfate to sodium ratio in bulk seawater. Subtraction of the sea salt contribution from the measured sulfate concentration yields the concentration of non-sea salt sulfur (nss-S) or nss-SO_4^{2-} (sulfur/sulfate).

Biogenic emissions of organic sulfur compounds, mainly dimethylsulfide (DMS), contribute to sulfur in Antarctic snow. DMS is oxidized to methanesulfonic acid (MSA) and sulfate in the marine atmosphere, which ultimately deposit on polar ice sheets. The ICP-MS technique measures total sulfur (nss-S after non-sea salt correction) in snow and ice samples (Sigl et al., 2016) which includes sulfur in MSA and sulfur in sulfate, while the IC technique measures only sulfate in the samples. To align the nss-S data (0–577 m and 1,300–1,911 m) with the nss-SO_4^{2-} concentrations (577–1,300 m), the MSA contribution needed to be subtracted from nss-S. MSA measurement (Saltzman et al., 2006) was performed on parts of the WDC core, but not at the same resolution as the major ions and elements. The average MSA concentration from the limited measurement during the Holocene is estimated to be 9.5 ppb (Santibáñez et al., 2018) and the equivalent amount of sulfur was subtracted from the measured nss-S to obtain nss-S in sulfate only. This approach of using average MSA concentration to represent the contribution to sulfur is justified by the fact that variability of MSA in Antarctic snow/ice in the Holocene is very small (Legrand et al., 1992; Saltzman et al., 2006). Nevertheless, it is possible, though unlikely, that some small events in the WDC volcanic record could have resulted from MSA variations. Following the MSA correction, nss-S concentrations were converted (multiplied by 2.996) to nss-SO_4^{2-} concentrations.

The nss-SO_4^{2-} flux of a year was calculated by multiplying the annual average concentration with the thinning-corrected layer thickness in water equivalent. The nss-SO_4^{2-} annual flux data resulting from those procedures and used to construct the volcanic record are shown in Figure 1.

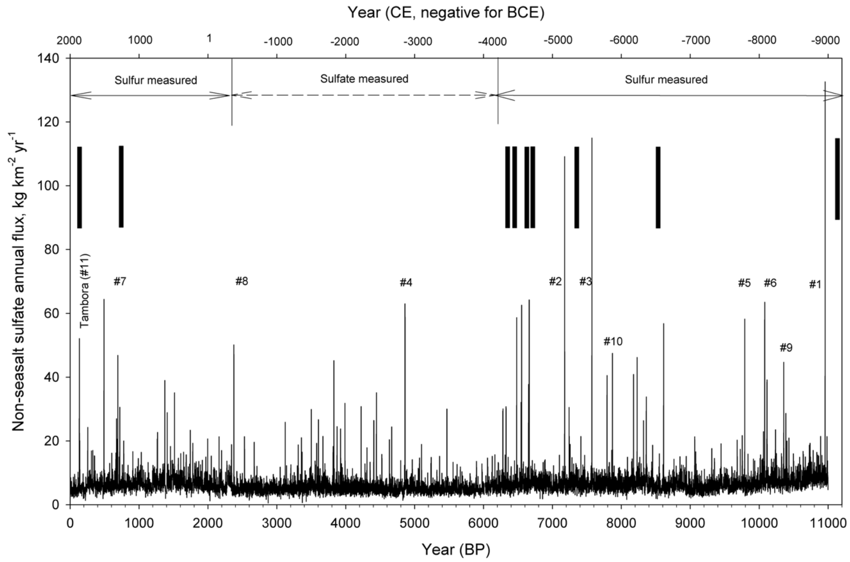

Figure 1. Annual non-sea-salt sulfate (nss-SO_4^{2-}) flux in the Holocene part of the WDC core. In sections where non-sea-salt sulfur (nss-S) was measured, rather than sulfate, contribution from methanesulfonic acid to nss-S was subtracted prior to nss-S conversion to nss-sulfate. The 11 largest volcanic events are labeled in order of rank by total volcanic flux. Vertical bars in the middle of the graph represent the largest nine volcanic events in the EDC96 ice core (Castellano et al., 2005). WDC, West Antarctica Ice Sheet Divide deep ice core.

3. Results and Discussion

3.1. Volcanic Signal Detection and Extraction

Volcanic contributions to sulfate in Antarctic snow are superimposed on a fluctuating background of nss-SO_4^{2-} originating from marine biogenic emissions. The background varies seasonally, but with very limited inter-annual variability in the absence of volcanic input (Cole-Dai, 2010). A method to distinguish volcanic sulfur/sulfate from the non-volcanic background needs to quantify the background and its variability. Previous studies on volcanic records from Antarctic ice cores have employed several such methods (e.g., Castellano et al., 2005; Cole-Dai et al., 2000; Ferris et al., 2011; Gao et al., 2008; Traufetter et al., 2004). Here, we use a method similar to that originally proposed by Traufetter et al. (2004) and refined by Sigl et al. (2015) to extract volcanic events from the WDC nss-SO_4^{2-} data. The following is a detailed description of the procedure to quantify the background and to extract volcanic signals from the nss-SO_4^{2-} data set.

The non-volcanic background nss-SO_4^{2-} flux was initially approximated with a 41-year (window) running median (RM) fit to the annual nss-SO_4^{2-} flux data. As a robust measure of the variability of the background in the presence of outliers, the median absolute deviation (MAD) from RM was obtained for each 41-year window. To detect volcanic events over the variable background, a relatively conservative (high) threshold of RM + 4 × MAD (Traufetter et al., 2004) was adopted. A year was deemed to contain volcanic fallout (volcanic year) if the annual nss-SO_4^{2-} flux exceeds this threshold. Next, after all years with flux above this threshold were removed, the reduced running mean (RRM) was calculated for the remaining years in the 41-year window in the time series. Detection and quantification of volcanic signals are minimally affected by the correction of MSA contribution to nss-S/nss-SO_4^{2-}, for the MSA concentration variation is small (Legrand et al., 1991) and not affected by the deposition of volcanic sulfur/sulfate.

Previous studies (Castellano et al., 2005; Cole-Dai et al., 1997; Ferris et al., 2011; Zielinski et al., 1994) on ice core volcanic records have demonstrated that the signal of a large volcanic event may span several consecutive years. The years immediately adjacent (prior and subsequent) to each detected volcanic year were examined to determine if deposits from the same volcanic eruption may be present. If the total nss-SO_4^{2-} flux of an adjacent year exceeds RM + 3 × MAD, that year is included as part of the same volcanic event and was removed and the RRM was re-calculated for remaining years in the 41-year window. The difference between total nss-SO_4^{2-} and RRM is the volcanic flux of a volcanic year. The volcanic flux of an event is the sum of

Table 1
Comparison of Number of Volcanic Events Detected During the Period of 1–2000 CE in Ice Cores From Several Antarctica Locations

Ice core	Location	Number of events	Event match with WDC	References
WDC	WAIS Divide	84		This work
WDC	WAIS Divide	89	66	Sigl et al. (2013)
DSS	Law Dome	43	32	Plummer et al. (2012)
SP04	South Pole	58	18	Ferris et al. (2011)
SDMA	Siple Dome	91	22	Kurbatov et al. (2006)
EDML	Dronning Maud Land	48	28	Traufetter et al. (2004)

volcanic flux of all consecutive years in that event and the number of years in that event is its duration. The high resolution of the chemical analysis and the high dating precision ensures that signals of eruptions close in time (2 or 3 years) are resolved and the eruptions are detected as separate events. For example, two unidentified eruptions in late 17th century CE were found to have occurred within 3 years of each other (1693 and 1695 CE) in a number of high-resolution Antarctic ice core records (Cole-Dai et al., 1997); these events are unambiguously detected in WDC, as Events 16 (1694 CE) and 17 (1697 CE). In rare cases, deposits of two or more eruptions occurring within a short period (1 year) can be mixed in the ice strata and it is possible that these may be detected as one event.

With the procedure described above, a total of 383 volcanic events were identified in the WDC nss-SO_4^{2-} data set and the volcanic flux and duration of each event was determined. The average duration is 1.6 years and the longest duration for any event is 5 years.

The detection threshold (RM + 4 × MAD) may be affected by the moving window size, particularly when more than one potential volcanic event may be in the window. We investigated the effect of window size on the detection of volcanic events by using alternative window sizes of 31 and 51 years. Use of the 51-year window did not yield results significantly different from those with the 41-year window. The 31-year window size resulted in 74 events that were not detected with the 41-year window in this 11,000-year period. Each of the additional events detected using the 31-year window was critically evaluated to minimize false positive detections due to years of high accumulation or unusually noisy background. Some volcanic years from the 31-year window were discounted because the accumulation was unusually high while the annual average concentration of nss-SO_4^{2-} was not unusual, or the flux of a suspected volcanic year did not appear outstanding in a period of noisy background. Following this procedure and using the 31-year window size on the Holocene WDC nss-SO_4^{2-} data set, 43 additional events were selected and added to the 383 detected with the 41-year window. No large or significant events were missed by the 41-year window detection and these additional events are relatively small in volcanic flux, as the mean volcanic flux of these additional events is 5.4 kg km^{-2} and the highest volcanic flux of the 43 additional events is no more than 10% of that (87.3 kg km^{-2}) of the 1815 CE Tambora eruption.

To validate the detection and quantitation method described above, we compared the volcanic events and volcanic sulfate flux in the period of 1–2000 CE to those identified in several Antarctica ice cores using various data sets and detection methods (Table 1). In particular, we compared the list of volcanic events during this period from this study with that by Sigl et al. (2013), who used a slightly different method (31-year window size and RM + 3 × MAD threshold) to detect and quantify volcanic events in the WDC nss-S concentration data set with sub-annual resolution. We identified events detected in one but not in the other method, examined the difference in the calculated flux for events identified in both methods, and compared the total volcanic sulfate flux for the 2000-year period. 84 events are detected in this study compared to 89 (Table 1) identified in Sigl et al. (2013), with 66 events in common between the two records. The median volcanic flux of the 23 events detected by Sigl et al. (2013) and not detected in this work is 7.7 kg km^{-2} (the median volcanic flux of 18 events not detected by Sigl et al. [2013] is similarly small [4.3 kg km^{-2}]), indicating that the difference in the detection methods involves only small events. For events that were detected by both methods, the volcanic flux calculated by Sigl et al. (2013) is 9.8% larger. The explanation for this discrepancy in flux may be that, in this study, an entire year had to be included or excluded as volcanic, whereas the

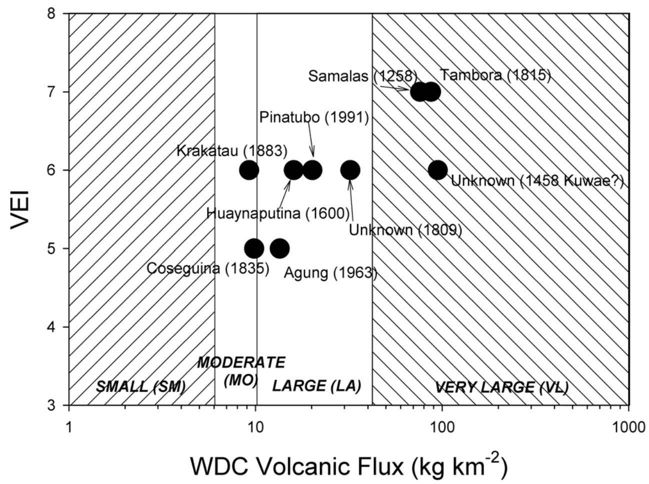

Figure 2. Relationship between eruption explosivity (VEI) and volcanic flux in the WDC ice core for several documented eruptions in the last 1,000 years. Numbers in parentheses are event/eruption years (CE). See text for the ranges of volcanic flux for *Very Large*, *Large*, *Moderate*, and *Small* events. VEI, Volcanic Explosivity Index; WDC, West Antarctica Ice Sheet Divide deep ice core.

sub-annual data set used by Sigl et al. (2013) allowed an event to begin or end any time during a year. For example, when determining the flux of the Tambora eruption, we selected the whole years of 1815, 1816, and 1817 as a single volcanic event and added the volcanic flux of these years to obtain the event flux (87.3 kg km^{-2}); in comparison, Sigl et al. (2013) determined the event duration to be 1815.4–1818.4 (decimals are for fractions, not months, in a year) and obtained a volcanic flux of 88.6 kg km^{-2}.

The detection and volcanic flux calculation method used in this study appear to adequately capture explosive eruptions with substantial sulfur emissions and quantify their volcanic flux. In this study, we refer to the volcanic signals detected in the ice core as "events," and use "eruption" or "eruptions" to mean the physical phenomenon. The application of the detection and quantification procedure to the WDC data set has yielded the WDC Holocene Volcanic (WHV2020) record, which contains 426 events with accurate chronology representing explosive volcanic eruptions in the Southern Hemisphere or the low latitudes with significant sulfur mass loading in the last 11,000 years. The events are numbered beginning with the most recent one. The event year is the first or the earliest year when the signal of the volcanic event appears in the ice core. This record can be used, when it is part of a composite of ice core records, for the evaluation of the climate impact of explosive volcanism in the Holocene.

3.2. Overview of the WDC Volcanic Record

The events in WHV2020 are categorized by the magnitude of the volcanic flux. Of the 426 events, 44 (10%) are *Very Large* volcanic events, with volcanic deposition or flux greater than 30.0 kg km^{-2}. About 28% of the total, or 118 events, are considered *Large*, with volcanic flux between 10.0 and 30.0 kg km^{-2}. Therefore, the confidence is high that 162 *Very Large* (VL) or *Large* (LA) events, 38% of all detected events, are included in WHV2020. Another 148 events (35%) with volcanic flux between 5.0 and 10.0 kg km^{-2} may be considered *Moderate* (MO). The remaining 117 events (27%) with volcanic flux smaller than 5.0 kg km^{-2} may be considered *Small* (SM) events. About 41% of all events are multi-year events (duration > 1 year). Approximately 90% (145 out of 161) of the *Very Large* and *Large* events are multi-year events.

We emphasize that the terms *Very Large*, *Large*, *Moderate*, and *Small* are only used for the magnitude of signals of the volcanic events in this record, not the magnitude of the eruptions. In fact, all events including those considered "*Small*" on this list are signals from explosive volcanic eruptions in the Southern Hemisphere or the low latitudes with significant sulfur mass loading, for only this type of eruptions is capable of leaving detectable signals in Antarctic ice cores (Cole-Dai, 2010).

The magnitude of explosive volcanic eruptions may be measured according to a number of scales including the semiquantitative Volcanic Explosivity Index (VEI), which are based on geological estimate of ejected materials (Newhall & Self, 1982). A study by Robock and Free (1995) found weak correlation between geological and/or geophysical volcanic indices and quantitative (aerosol mass) ice core records. The VEI ratings and WDC volcanic flux of several well-known eruptions in the last several hundred years in Figure 2 show that, despite an apparently positive correlation, the relationship is characterized by large uncertainty. For example, the volcanic flux of five eruptions (Pinatubo, Krakatau, Huaynaputina, Unknown Eruption (1809), and Unknown Eruption (1458)) with VEI of 6 ranges from 9 kg km^{-2} (MO) to 95 kg km^{-2} (VL). Further, as mentioned previously, the magnitudes of ice core signals are strongly influenced by factors such as sulfur content of erupted materials, volcanic aerosol transport, deposition, signal preservation and detection, while the eruption magnitude is affected by factors (e.g., location and type of volcanoes and eruption style) completely unrelated to those for the ice core signals. Therefore, a quantitative relationship should not be expected between the explosivity of eruptions and signals in ice cores.

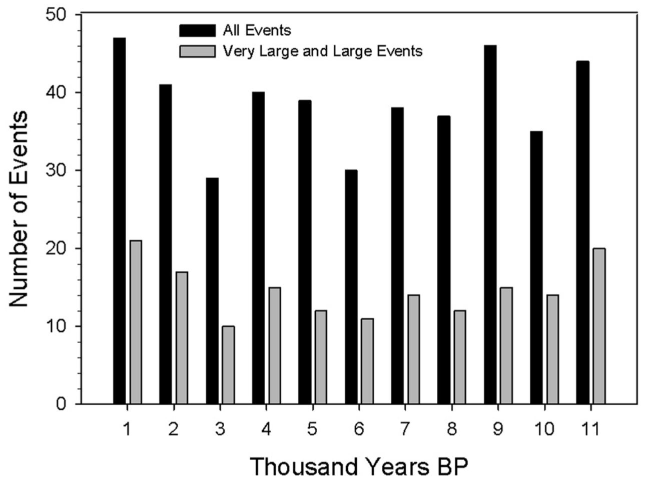

Figure 3. The number of all events (dark bars) by millennium in the WDC Holocene record. The number of *Very Large* and *Large* (volcanic flux ≥ 10.0 kg km^{-2}) events (gray bars) tracks closely the number of all events (r^2 = 0.835). WDC, West Antarctica Ice Sheet Divide deep ice core.

3.3. Frequency of Volcanic Eruptions

The average frequency of volcanic events in WHV2020 is 38.7 events per 1,000 years. In comparison, Castellano et al. (2005) found a total of 96 volcanic events during the Holocene in the EDC96 ice core drilled in 1996–1999 at Dome C, East Antarctica, with an average of 8.3 events per millennium. The much smaller number of eruptions in EDC96 may be attributed to fewer *Moderate* and *Small* events resulting from a high volcanic detection threshold in the EDC96 core (see later discussion).

Castellano et al. (2005) found many more volcanic events in the most recent two millennia (21 and 12 in First [1000–2000 CE] and Second [1–1000 CE] Millennium BP, respectively) than the millennial average (8.3) of the Holocene. In contrast, in the WDC record, only the number of events in the First Millennium BP (47) and the number (44) in the oldest millennium (11th Millennium BP) are noticeably but only slightly larger than the millennial average (38.7). The number in the Second Millennium BP (40) is not significantly higher than the millennial average. Indeed, no apparent trend in the number of events per millennium is detected (Figure 3) during the Holocene in WDC.

To facilitate the comparison of volcanic events recorded in ice cores from locations under different glaciological conditions (e.g., snow accumulation rate) for deposition and preservation of volcanic fallout, Cole-Dai et al. (1997) proposed to use the ratio (f/f_{Tambora}) of the volcanic flux of an event to that of the 1815 CE Tambora eruption in the same ice core as a measure of the relative magnitude of ice core volcanic signals. The volcanic flux of each of the 10 largest events (Table 2) is greater than that of Tambora (87.3 kg km^{-2}) which is ranked Number 11. Only two of the largest 10 and Tambora are in the second half (<5.0 ka BP) of the Holocene, while four are in the period between 10 and 11 ka and three are found in the 7–8 ka period. The signal of the 1258 CE eruption of Samalas (Lavigne et al., 2013) has been found to be the largest or the second largest in the last 2,000 years in several Antarctic ice cores (Castellano et al., 2005; Cole-Dai et al., 2000; Traufetter et al., 2004). In WHV2020, the Samalas event is ranked Number 16 (f/f_{Tambora} = 0.87), smaller than the 1459 CE event (f/f_{Tambora} = 1.09) and Tambora. The relatively (to Tambora) small Samalas flux in WDC is probably the result of variation of ice core volcanic signals due to factors such as atmospheric transport of volcanic aerosols to specific location in Antarctica, deposition efficiency, and signal preservation in the snow strata.

Table 2
The Largest Events by Flux in the Holocene Volcanic Record From the WDC Ice Core

Rank	Event number	Start year (BP)	Start year (CE)	Duration (year)	Sulfate flux (f, kg km^{-2})	f/f_{Tambora}
1	426	10,957	−9007	3	182.1	2.09
2	272	7,177	−5227	3	160.9	1.84
3	288	7,572	−5622	3	153.7	1.76
4	193	4,860	−2910	2	110.8	1.27
5	390	10,115	−8165	5	108.2	1.24
6	389	10,080	−8165	2	105.7	1.21
7	26	491	1459	3	94.9	1.09
8	99	2,376	−426	3	92.3	1.06
9	400	10,356	−8406	3	91.0	1.04
10	292	7,793	−5843	3	88.3	1.01
11	10	135	1815	3	87.3	1.00

Note. The Tambora eruption (1815 CE) is ranked 11. Negative CE numbers are for BCE.
Abbreviation: WDC, West Antarctica Ice Sheet Divide deep ice core.

In the EDC96 record, volcanic flux of the nine largest events is comparable to or greater than that of Tambora (f/f_{Tambora} > 0.9, f_{Tambora} = 39.3 kg km^{-2}). A very large event (41.0 kg km^{-2}, f/f_{Tambora} = 1.04) is found at 11,162 (±200) year BP, close to the start year (10,957 years BP) of the largest WDC event (Event 426). The nine largest EDC96 events are marked in Figure 1, where they appear to correspond to some of the largest events in WHV2020. The similar number of events with extraordinarily high sulfur mass loading in these two records suggests that all VL and LA events are probably captured in both EDC96 and WDC (Figure 1). Significant differences between these ice core volcanic records are likely in the number and deposition flux of MO and SM events. The explanation for the differences in the total number of events and volcanic flux may be that detection of *Moderate* and *Small* events depends critically on the non-volcanic background and its variability in individual ice cores (i.e., large variations in the EDC96 background result in high detection threshold and, consequently, fewer detected *Moderate* and *Small* events).

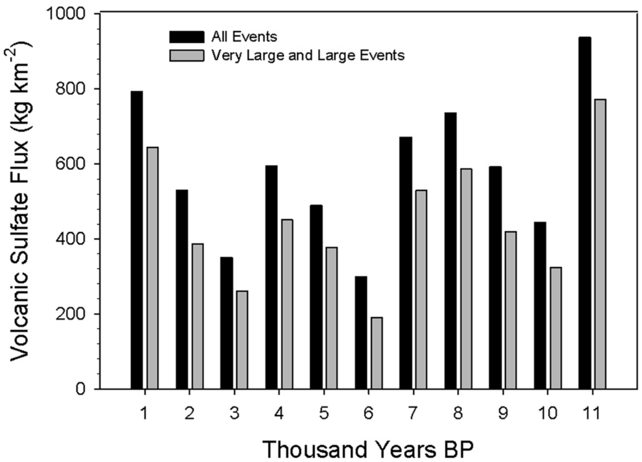

Figure 4. The total volcanic flux of all events (dark bars) by millennium in the WDC Holocene record. The volcanic flux (gray bars) of *Very Large* and *Large* events (volcanic flux ≥ 10.0 kg km^{-2}) accounts for 75% of all volcanic flux and is highly correlated with the total flux (r^2 = 0.996). WDC, West Antarctica Ice Sheet Divide deep ice core.

Kurbatov et al. (2006) found 124 volcanic events in a Siple Dome, West Antarctica ice core covering the last 12,000 years. Because the Tambora signal was not detected in the Siple Dome (SDMA) core, due to poor core quality, it is difficult to compare the magnitude of signals in that core with those in WDC. Nonetheless, large events in the Siple Dome record may be compared to those in the WDC record. The seven events in SDMA with highest sulfate concentrations are dated at 7,831; 2,278; 5,988; 4,768; 691; 11,332; and 6,404 years BP, respectively. Due to differences in dating accuracy and precision, it is not possible to determine if the same events are detected in WDC.

3.4. Volcanic Flux

The climate impact of volcanic eruptions is mainly derived from the radiative forcing of volcanic aerosols (Robock, 2000; Timmreck et al., 2016). The impact may vary, given a certain magnitude of forcing, depending on the state of the climate system at the time of the eruptions (Wigley et al., 2005); in addition, regional variation in climate response is common (Shindell et al., 2003). Nonetheless, climate response is generally positively related to the forcing magnitude or atmospheric mass loading of volcanic aerosols (Sigl et al., 2015). It has been recognized (Zielinski, 1995) that ice core volcanic flux can be a robust proxy of atmospheric mass loading of volcanic aerosols from explosive eruptions.

The highest cumulative volcanic sulfate flux (937 kg km^{-2}) in a millennium is found (Figure 4) in the 11th Millennium BP (10–11 ka), which is not surprising, given the large number of events and the large number of VL events in the millennium (Figure 1). This is more than three times as large as the smallest cumulative volcanic flux (300 kg km^{-2}) in the Sixth Millennium BP (Figure 4). On average, the flux of VL and LA events (volcanic flux ≥ 10.0 kg km^{-2}) accounts for 75% of the total detectable volcanic flux in a millennium. Moreover, the flux of VL and LA events is closely correlated with the total flux (r^2 = 0.996). A similarly close correlation (r^2 = 0.756) is found between the total volcanic flux and the number of VL and LA events. One implication of this close correlation between the total volcanic flux and the measures of VL and LA events may be that, on a millennial timescale, the climate impact of volcanism is dominated by eruptions with extraordinarily high sulfur mass loadings. The data show that volcanic sulfur/sulfate is found in approximately 6.1% (674 out of 11,056) of the years in the Holocene. This suggests that direct radiative forcing by explosive volcanism is limited to less than 1 year in a decade on average.

3.5. Comparison With Non-Ice Core Records

Crosweller et al. (2012) recently compiled a comprehensive global database of Quaternary Large Magnitude Explosive Volcanic Eruptions (LaMEVE). Only eruptions with a magnitude *M*, approximately equivalent to VEI, of 4.0 or greater and associated with known volcanoes are included in the LaMEVE database. The database contains 2,414 eruptions in the Holocene by approximately 3,000 known volcanoes.

To assess the ability of the WDC ice core to record signals of past eruptions, a comparison is made here between WHV2020 and the Holocene portion of the LaMEVE database. The magnitude of eruptions (*M*) in LaMEVE is a measure of the mass of materials ejected (explosivity), while the event magnitude (volcanic sulfate flux) in ice cores is a quantitative measure of volcanic aerosol mass directly related to the climate impact of eruptions. A highly explosive eruption, with a large *M* in LaMEVE, may not generate massive aerosols to impact the climate, while an eruption injecting massive aerosols may be only moderately explosive. Despite the difference in what is measured in LaMEVE and WHV2020, a broad, order-of-magnitude comparison of the two records on the number or frequency of unusually large eruptions or events may allow an assessment of how well either one captures past eruptions and relative to each other.

We searched the LaMEVE database for the number of eruptions in the Holocene. Redundant eruptions, which are eruptions by the same volcano in the same year and are assumed to be capable of producing only

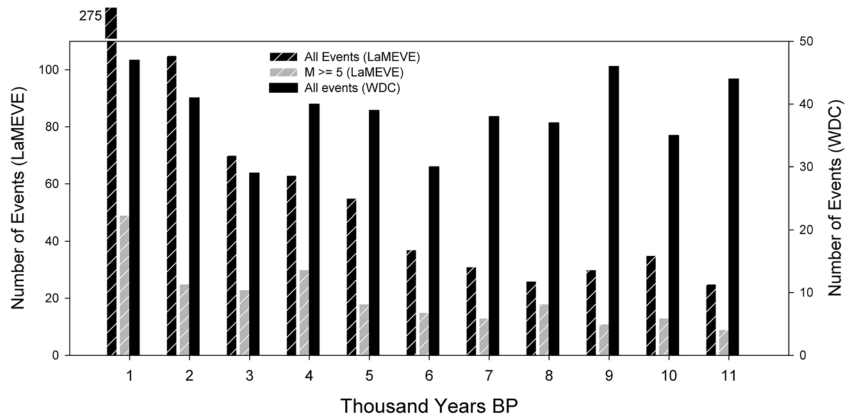

Figure 5. The number of events by millennium in the LaMEVE data set (Crosweller et al., 2012): dark hatched bars, total events; gray hatched bars, major events ($M \geq 5$) during the Holocene. The numbers of total events by millennium in the WDC record shown in dark bars are not correlated with the numbers in the LaMEVE data set. WDC, West Antarctica Ice Sheet Divide deep ice core.

one event signal in ice cores, were combined into a single event. When the two records are compared by millennium, no significant correlation is apparent between the number of events in the LaMEVE database and the number of events recorded in WDC (Figure 5). The numbers of events in the most recent millennia in the LaMEVE database are much higher than in older millennia (Figure 5), due to under-recording of older events (Brown et al., 2014; Rougier et al., 2018). The under-recording is much less (Figure 5) in major events ($M \geq 5.0$). Despite the reduced under-recording of extraordinarily large eruptions in older millennia, the correlation between the number of WDC events and the number of major events in LaMEVE is not significant.

Rougier et al. (2018) analyzed the LaMEVE data set and modeled the exceedance probability of large volcanic eruptions in the last 100,000 years. They calculated a return period of 1,200 years (95% confidence interval: 680, 2,100 years) for eruptions with $M \geq 7.0$. This estimated return period is consistent with the event frequency for very large events in the WHV2020 record (Table 3). The return period for events with volcanic flux (f/f_{Tambora}) comparable to and greater than that of Tambora is approximately 1,000 years (11 out in 11,000 years) with a range of 790 years ($f/f_{\mathrm{Tambora}} \geq 0.90$) to 1,800 years ($f/f_{\mathrm{Tambora}} \geq 1.10$).

3.6. Volcanic Events in the 17th Century BCE

The volcanic eruption on the eastern Mediterranean island of Thera (Santorini) some 3,600 years ago was an important milepost in the development of Near Eastern and Egyptian civilizations in the Late Bronze Age (Manning et al., 2006). The date or year of the eruption, crucial to the synchronization between these Eastern Mediterranean civilizations, has been a topic of considerable debate (Manning et al., 2014; McAneney & Baillie, 2019). Radiocarbon dates of archeological samples and buried wood from Santorini indicate that the

Table 3
Event Frequency and Return Period for Very Large Volcanic Eruptions (Volcanic Flux Comparable to or Greater Than That of Tambora) During the Holocene in the WDC Volcanic Record

Data source	Relative flux (f/f_{Tambora})	Number of events	Return period (years)	References
WHV2020	≥0.90	14	~790	This work
WHV2020	≥1.00	11	~1,000	This work
WHV2020	≥1.10	6	~1,800	This work
LaMEVE			1,200 (680–1,200)	Rougier et al. (2018)

Note. The return period for similarly large eruptions ($M \geq 7$) in the LaMEVE database is reported by Rougier et al. (2018). Abbreviations: LaMEVE, Large Magnitude Explosive Volcanic Eruptions; WDC, West Antarctica Ice Sheet Divide deep ice core.

Table 4
Prominent Volcanic Events in the Period of 17th to 16th Century BCE in the WDC Volcanic Record

In WDC			
First year (BCE)	Duration (years)	Volcanic flux (f, kg km^{-2})	Relative flux (f/f_{Tambora}[a])
1657	4	40.0	0.46
1629	2	18.2	0.21
1612	3	17.0	0.19
1551	2	37.0	0.42
In Greenland			
First year (BCE)	Duration (years)	Peak sulfate concentration (C, ppb)	Relative concentration (C/C_{Tambora}[b])
1653	2	245.9[c]	0.75
1627	2	109.5[c]	0.27
1610	1	~50[d]	~0.17

Note. Also listed are volcanic events in the period of 17th to 16th Century BCE in the GIPS2 and NGRIP (Greenland) ice cores.
Abbreviation: WDC, West Antarctica Ice Sheet Divide deep ice core.
[a]The Tambora sulfate flux is 87.3 kg km^{-2} in WDC (this work). [b]The peak sulfate concentration of the 1815 CE Tambora eruption is 285 ppb in a 2007 Summit, Greenland ice core (Cole-Dai et al., 2013). [c]Peak sulfate concentrations in the GISP2 core reported by Zielinski et al. (1994) are for samples with a 2-year/sample time interval. [d]Sulfate concentration estimated from H^+ concentration in the NGRIP core (McAneney & Baillie, 2019) measured with ECM.

eruption occurred in the second half of the 17th century BCE (Friedrich et al., 2006; Manning et al., 2006). The radiocarbon ages are echoed by tree-ring (LaMarche & Hirschboeck, 1984; Salzer & Hughes, 2007) and Greenland ice core (Hammer, 1977; Hammer et al., 1987; Vinther et al., 2006) evidence of unusually explosive volcanic eruptions in this time period.

However, all the techniques to investigate past volcanic eruptions in tree-ring and ice core records carry uncertainties and ambiguities regarding the age and nature of events contained in the substrates and materials. As a result, significant disagreements exist regarding the Thera eruption date and, consequently, its impact on the chronology and interaction of the Eastern Mediterranean civilizations (Manning et al., 2014). In a recent re-evaluation of the available tree-ring and ice core data and evidence, McAneney and Baillie (2019) conclude that three large volcanic eruptions occurred in the 17th century (1700–1600) BCE, with ice core dates of 1653, 1627, and 1610 BCE, after application of proposed revision (Baillie & McAneney, 2015) to the GICC05 timescale (Vinther et al., 2006) for Greenland ice cores. These investigators contend, however, that none of the volcanic horizons in the mid to late 17th century BCE period is likely that of the Thera eruption. The basis for this contention is that the 1653 and 1610 BCE volcanic signals are near the outer boundaries of radiocarbon-dated age range of Thera artifacts, and that tephra matching that of an Alaskan volcano (Aniakchak, 56.9°N, 158.2°W) was found in the ice containing the 1627 BCE event (Coulter et al., 2012), while no volcanic tephra with chemical composition matching Thera ash has been found in the ice layers of these volcanic horizons.

A very large (volcanic flux of 40.0 kg km^{-2}, $f/f_{\text{Tambora}} = 0.46$) and two large (18.2 and 17.0 kg km^{-2}) volcanic events are found in the mid to late 17th century BCE period in the WDC record (Table 4 and Figure 6). The maximum dating uncertainty of the annual-layer-counting dated part of WDC is 0.5% (Sigl et al., 2016); in parts of the core where annual layer thickness was at least 10 cm, the dating uncertainty is as low as 0.1%. The expected uncertainty in this time period (3600–3550 BP) is close to 0.3%, or ±11 years. The dates, 1657, 1629, and 1612 BCE, of the events in WDC are synchronous, given the age uncertainty, with those in the Greenland ice cores (Table 4 and Figure 6) according to the proposed revised GICC05 timescale. These data of synchronous appearance in bipolar (Greenland and Antarctica) ice core records indicate that each of the three eruptions resulted in the distribution of volcanic sulfate over both hemispheres and subsequent deposition on the ice sheets. According to available ice core evidence (e.g., Langway et al., 1988) and atmospheric observations (Stothers, 1996), only eruptions in the low latitudes are capable of simultaneously elevating sulfate levels in both Greenland and Antarctica ice cores. This suggests that Thera, with the latitudinal

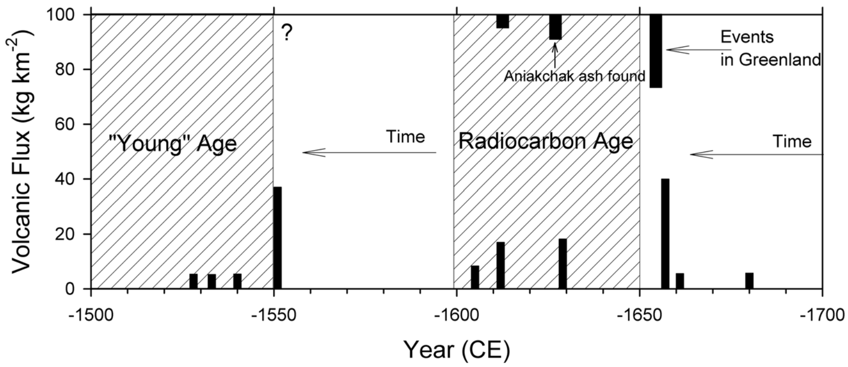

Figure 6. Volcanic events in the periods of mid to late 17th Century BCE (radiocarbon age range for the Thera eruption) and late 16th Century BCE ("Young" age for Thera) in WDC. Three volcanic events in Greenland ice cores (vertical bars on top; bar size proportional to the magnitude of the volcanic signals in the ice cores) match in date the three large WDC events in the period of mid to late 17th Century BCE. WDC, West Antarctica Ice Sheet Divide deep ice core.

location of 36.4°N, would be incapable of leaving a detectable signal in Antarctic ice cores. Recent modeling studies (Toohey et al., 2016, 2019), however, suggest that volcanic aerosols of extraordinarily large eruptions in the mid or high latitudes of one hemisphere (e.g., Northern Hemisphere) may be distributed, on a quantitatively limited basis, to the opposite hemisphere. The Aniakchak eruption, while leaving tephra in the ~1627 BCE ice layers in Greenland, may not have contributed significantly to the sulfate signal, if its erupted materials were sulfur-poor.

In rare instances, simultaneous (in the same year) eruptions by at least one volcano in the Southern Hemisphere (south of 20°S) and one in the Northern Hemisphere (north of 20°N) may also produce bipolar signals in ice cores. In such a scenario, the Thera eruption may have been responsible for, or have contributed to, one of the three signals in the Greenland ice cores. While it is difficult to compare signal magnitude in WDC to those in Greenland ice cores, due to the lack of high-quality volcanic flux data from GISP2 and GRIP cores, a close examination of the Greenland ice core data in summary by McAneney and Baillie (2019) and the WDC data (Table 4) may provide clues to the location of the volcanoes responsible for these eruptions. First, if Thera is solely responsible for one of the signals in the Greenland cores, while another eruption in the mid or high latitudes of the Southern Hemisphere left a contemporaneous signal in WDC, the magnitude of the two signals (relative to that of Tambora) in Greenland and Antarctica ice cores would be expected to be quite different from each other. The relative magnitudes of the 1629 BCE ($f/f_{Tambora}$ = 0.21) and 1612 BCE ($f/f_{Tambora}$ = 0.19) events in WDC are similar to those (0.27 and ~0.17, respectively) in the Greenland ice cores (Table 4), suggesting that these were both low latitude eruptions. This scenario appears to be quite similar to the bipolar ice core signals of a much recent (1809 CE) unidentified eruption in the low latitudes (Cole-Dai et al., 2009). Second, if the Thera eruption added to the sulfate fallout to Greenland by an eruption in the low latitudes, the signal (relative to that of Tambora) in a Greenland ice core would be expected to be significantly larger in magnitude than that in an Antarctica ice core. Apparently, that is not the case for the 1629 and 1612 BCE events. In the case of the 1657 or 1659 BCE event, the relative signal magnitude in GISP2 ($C/C_{Tambora}$ = 0.75) is significantly larger than that ($f/f_{Tambora}$ = 0.46) in WDC. Therefore, it is possible, although unlikely, that Thera erupted in 1654 ± 2 BCE and contributed to the volcanic signal in Greenland ice layers immediately following the eruption, while another explosive eruption occurred in the low latitudes.

The data from WDC and Greenland ice cores support the conclusion that at least three major volcanic eruptions took place in mid to late 17th century BCE. The fact that the signals are also found in a well-dated Antarctica ice core is strong evidence that none of these three is the Thera eruption. However, the same data do not exclude the possibility, albeit small, that the Thera eruption may have contributed to the earliest of the three signals in Greenland ice cores. Therefore, the balance of evidence from bipolar volcanic sulfate deposition and the tephra composition in Greenland ice cores supports the contention that the Thera eruption

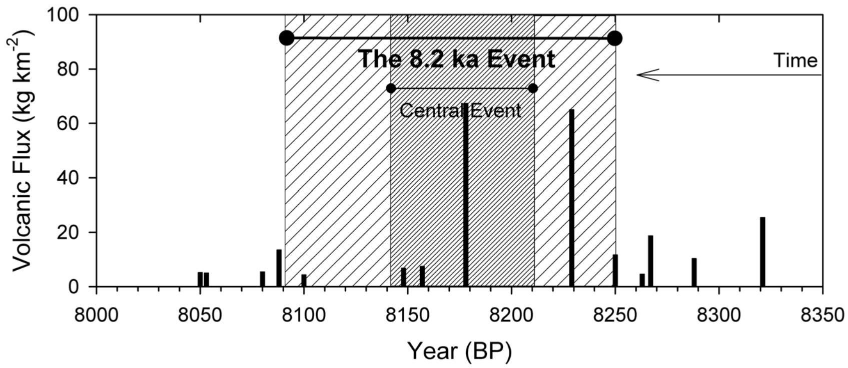

Figure 7. Volcanic events in the period of the 8.2 ka climate event in the WDC core. The duration of the 8.2 ka event is approximately 160 years and the central part of the event is about 70 years (Thomas et al., 2007). WDC, West Antarctica Ice Sheet Divide deep ice core.

did not take place during the time period of mid to late 17th century BCE. It is also possible that the eruption occurred at that time but did not inject significant amounts of sulfur into the stratosphere.

Pearson et al. (2018) dated a frost-ring event in a tree-ring record and suggested, based on a new interpretation of the radiocarbon calibration curve, that a major volcanic eruption took place at or near 1560 BCE, in a date range (the "young" age of the Thera eruption) favored by some archaeologists based on interpretation of archeological evidence and reservations about the integrity of radiocarbon samples (McAneney & Baillie, 2019). The WDC data suggest that volcanic signals in Greenland ice cores during the period of 1570–1500 BCE are very nearly all from Northern Hemisphere eruptions, as only one major volcanic eruption may have taken place in the low latitudes at 1552–1551 BCE (Table 4 and Figure 6) and could have left a detectable signal in Greenland. These recent findings seem to indicate that it may be beneficial to look for tephra from the Thera eruption in the time period of 1570–1500 BCE in Greenland ice cores.

3.7. Volcanic Events and the 8.2 ka Climate Anomaly

Greenland ice cores record a major cold climate episode (Alley et al., 1997) in the Eighth Millennium BP (8–9 ka). This climate anomaly, known as the 8.2 ka event, began at approximately 8,250 years BP (GICC05) and lasted 160 years (Kobashi et al., 2007; Thomas et al., 2007). The coldest part of this event at the central portion of the 160-year event lasted approximately 70 years, 8,212–8,141 BP (Thomas et al., 2007).

In WHV2020, a number of *Very Large* and *Large* events are seen close to and during the time period of the 8.2 ka event (Figure 7). In particular, one VL event with volcanic sulfate deposition flux of 65.1 kg km^{-2} ($f/f_{\text{Tambora}} = 0.75$) and a duration of 4 years occurred (8,229 BP) in the early part of the 8.2 ka event; another VL event (67.3 kg km^{-2} flux and 3 years in duration) occurred 51 years later (8,178 BP), during the central part of the 8.2 ka event. In addition, three LA events (8,288, 8,267, and 8,250 BP) and one SM (small) event (8,263 BP) are detected in the 40-year period immediately before the start of the 8.2 ka event (Figure 7).

The current hypothesis of the origin of the 8.2 ka event (Thomas et al., 2007) is that the final stage of deglaciation in North America resulted in rapid discharge of freshwater into the North Atlantic, thereby reducing the heat flux from the North Atlantic to the atmosphere. The decrease in atmospheric temperature over Greenland may have been as much as 6°C or 7°C (Alley et al., 1997; Leuenberger et al., 1999). Because major volcanic eruptions are capable of depressing temperature by as much as 3°C or 4°C for a very short time period (up to 3 or 4 years), the VL and LA volcanic events, if occurring in the low latitudes during the 110-year period (8,288–8,178 BP), would not be mainly responsible for the initiation of the 8.2 ka event or the magnitude of cooling. However, the eruptions could have contributed to the initiation of the event and exacerbated the climate impact caused by the meltwater discharge. In addition, the number of VL and LA volcanic events during the period in the WHV2020 record from an Antarctica ice core suggests that the volcanic impact on the climate was likely global and the 8.2 ka climate anomaly may not have been limited to the North Atlantic (Alley & Ágústsdóttir, 2005; Wiersma & Renssen, 2006) or even the Northern

Hemisphere. The suggestion that these volcanic eruptions may be connected to the 8.2 ka event is speculative. Nonetheless, the occurrence of two of the largest volcanic events in the Holocene at this time period suggests that volcanism should not be overlooked as among the potential drivers for this climate event. Systematic examination and modeling work are needed to investigate and establish such a connection.

4. Conclusions

The WAIS Divide, Antarctica deep ice core has yielded long and detailed climate and paleoenvironmental records. The comprehensive WDC volcanic record (WHV2020) comprises signals of 426 explosive volcanic eruptions in the Southern Hemisphere or the low latitudes with significant aerosol mass loadings during the Holocene. Comparison of WHV2020 with existing volcanic records from ice cores indicates that the new record is of the highest quality of all ice core volcanic records, owing to the high-resolution chemical measurement of the ice core and the exceptionally accurate WDC timescale. A relatively large fraction (38%) of the events are *Large* and *Very Large*, with deposition of volcanic sulfate greater than 10 kg km^{-2}. The climatic impact of volcanism during the Holocene is probably dominated by the extremely explosive eruptions represented by these large ice core events. No apparent trend is found regarding the frequency (number of eruptions in a millennium) of volcanic eruptions during the Holocene. Contrary to evidence in previous ice core records in which the eruption frequency appears to be the highest in the most recent millennium (1000–2000 CE), the number of major volcanic eruptions in this millennium in WHV2020 is only slightly higher than the millennial average of the Holocene. No apparent correlation is found between the number of all events (representing eruptions with significant aerosol mass loading) in WHV2020 and the number of major and moderate eruptions in a recently compiled global Quaternary volcanism database (LaMEVE), while the return period (approximately 1,000 years) of eruptions with volcanic flux comparable to or greater than that of Tambora is consistent with that found in the LaMEVE data set. We searched for volcanic events in the second half of the 17th century (1700–1600) BCE that may be linked to the suspected eruption of the Thera volcano in the eastern Mediterranean. Signals of three major volcanic events in WDC during this period are synchronous with three volcanic eruptions detected in Greenland ice cores, suggesting that these are likely eruptions in the low latitudes and none should be attributed exclusively to Thera. Several explosive eruptions with very high aerosol mass loading during and shortly before the onset of a climactic episode, the so-called 8.2 ka event, early in the Holocene, may have contributed to the initiation, duration, magnitude, and global coverage of the cold episode.

Data Availability Statement

Data sets for this research are available at the Open PRAIRIE Public Research Access Institutional Repository and Information Exchange of South Dakota State University.

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