Reconstructing the History of Volcanic Forcing of Climate from Polar Ice Cores

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1. Introduction

Explosive volcanic eruptions can cause profound climate variability by injecting large quantities of sulfur into the atmosphere. Released sulfur gases oxidise to form sulfate aerosols, which reflect sunlight, thereby inducing a 1 – 5-year cooling effect on the Earth's surface (Schurer et al., 2013). Radiative forcing is a term used to describe when a difference in energy enters or leaves the Earth's atmosphere, leading to a change in the Earth's climate (Forster, 2003). Radiative forcing from volcanic eruptions is greatest when these aerosols reach the stratosphere, where the aerosols can be suspended for several years before moving poleward and deposited (Burke et al., 2019). Before the Industrial Revolution, volcanic eruptions were the dominant control of the global climate (Stevenson et al., 2016). Furthermore, volcanic forcing influences the same components of the Earth's system that control sensitivity to CO_2 (Soden et al., 2002). As a result, the climatic impacts of volcanoes are essential in understanding past climates and the future of the current climate change crisis.

The key parameters that dictate the impact of volcanic eruptions are under-constrained, which provides an opportunity for further research. This requires distinguishing between forced external drivers, such as volcanic eruptions, and internal climate variability, which is dependent on accurate records of volcanic radiative forcing (Schurer et al., 2013; Toohey & Sigl, 2017). Current state-of-the-art models are based on ice cores from Greenland and Antarctica, which contain sulfur concentration peaks that provide information about volcanic forcing for the past 2000 years (Crowley and Unterman, 2012; Gao et al., 2008). The sulfur peaks give information on the magnitude, timing and location of volcanic eruptions, extending beyond the instrumental record that covers only the past 150 years (Burke et al., 2019; Sigl et al., 2013).

Despite sulfur being the primary determinant of radiative forcing, both latitude and the season in which the eruption took place also play crucial roles in influencing the resultant climate effects (Marshall et al., 2019). However, current models largely ignore seasonality in their reconstruction and assign unknown volcanic eruptions an eruption date of January 1st or July 1st, which introduces significant uncertainty (Crowley and Unterman, 2013; Toohey and Sigl, 2017). This is particularly important at mid–high latitudes where the change in incoming solar radiation (insolation) between summer and winter months is much greater than in lower latitudes, resulting in a difference in aerosol formation, transport and deposition (Kravitz & Robock, 2011). Furthermore, Marshall et al. (2020) simulated that winter eruptions generate greater radiative forcing because aerosols peak during the summer due to a 6-month aerosol transport time when solar insolation is highest. Therefore, it is evident that seasonality is an integral part of the radiative forcing caused by volcanic eruptions.

My project aims to improve further the inclusion of seasonality of volcanic eruptions in Paleoclimate Model Intercomparison Project forced datasets, which aim to understand the climate system better. It will build upon methodologies conducted by Oppenheimer et al. (2018), who compared seasonally varying aerosol concentrations relative to sulfur peaks in the NEEM-2011 S1 ice core to identify the season and duration of the 939 CE Eldgja eruption, see Figure 1. The timing of annual frequency peaks of chosen aerosol ions can be calculated using high resolution snow data to constrain the timing of unknown volcanic eruptions in the past which are recorded as sulfate peaks in the NEEM-2011 S1 ice core.

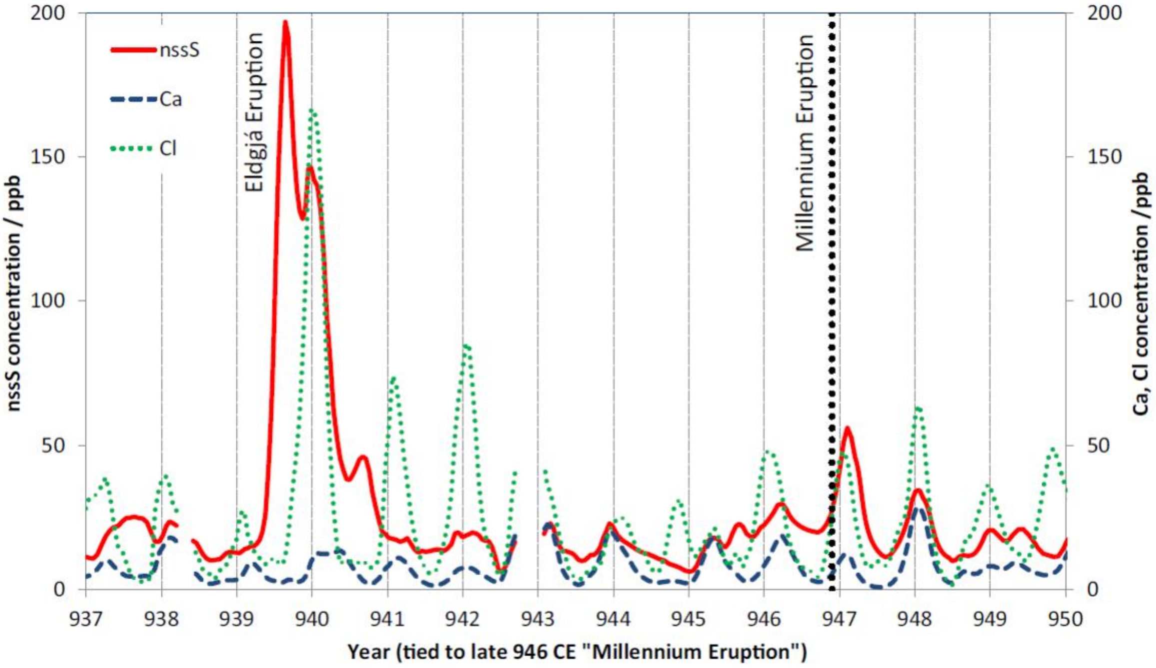

Figure 1

Time concentration graph of chloride, calcium and sulfur records from Oppenheimer et al (2018), who used seasonal variations in chloride and calcium concentrations to propose that the 939 CE Eldgja eruption began in the spring and continued until autumn 940 CE. Evidenced by the timing of chloride, calcium and sulfate peaks in the NEEM-2011 S1 ice core.

My research builds upon a computer model based on the method used by Oppenheimer et al. (2018). The computer model was produced during a fourth-year dissertation project by Heather Gore (2021) – a University of St Andrews graduate, which intended to systematically calculate the season of unknown eruptions over the past 2000 years.

2. Methodology

2.1 Site

A dataset of irregularly spaced measurements of 12 chemical species from surface snow measurements was taken at the Summit Greenland Environmental Observatory 72° N, 38° W (Chellman, 2009) from August 2003 to August 2013, see Figure 2. This was to determine annual frequency peaks of the seasonally varying ion concentrations in the snow. The site was chosen due to its stable conditions year-round to allow for accurate data collection. It remains below 0 degrees and is at an elevation of 3250 m above sea level, where annual snow accumulation rates are low as opposed to lower elevations, which are subject to more post-depositional changes to the snow (Johnsen et al.,1992).

The ice core data was collected from the North Eemian Ice Drilling (NEEM) camp, shown in Figure 2, at 77N̊, 51 W̊ 650km from Summit (Sigl et al.,2015). This site has a higher snowfall accumulation rate than Summit.

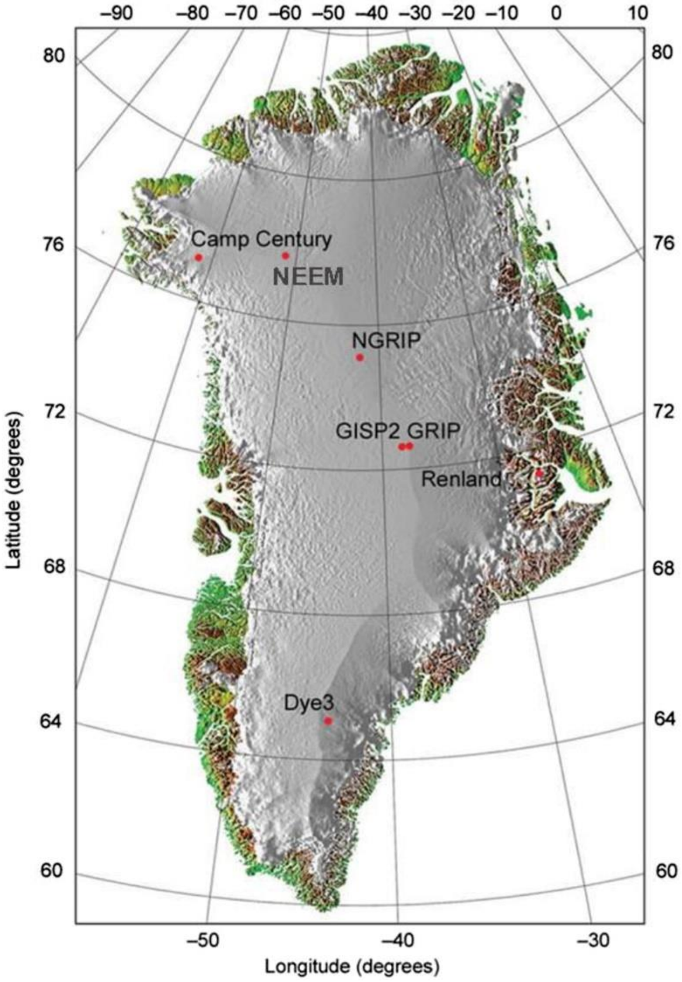

Figure 2

Location of sample areas in Greenland. Summit camp (72° N, 38° W) where snow samples are taken and North Greenland Eemian Ice Drilling (NEEM) Camp (77˚N, 51˚ W) where NEEM-2011 S1 ice core was drilled. From Kang et al (2015).

2.2 Calibration

I loaded the snow data set into MATLAB (a mathematical-based computer language). I selected a subset of data (2007 to 2012) with sampling intervals of a week or less, and outliers were removed. I followed the previous computer script, which contained many unanswered questions and problems I recorded and corrected. Each species was plotted against time, and the species that showed a cyclical pattern and had abundant literature available were selected: Na^+, Cl^-, Mg^{2+}, Ca^{2+}, NH^{4+}, $SO_4{}^{2-}$ and NO^{3-} signals. A reduced dataset was formed by averaging the samples within each week to compare each species accurately. Calcium (Ca^{2+}) was shown in Gore's (2021) project to be one of three species with a high amplitude peak at a frequency of 1 per year, significant to 95% confidence. This was calculated by conducting a fast Fourier transform (FFT) on the data set. This mathematical function converts a signal into a composite of sine and cosine waves, which allows one to visualise the signal in terms of the frequencies that make up the signal. In other words, there was a significant peak in Ca^{2+} concentration at the same time every year over the sampling period. Due to the stability of the Earth's system, it is assumed that the seasonality of the ion has been constant over the past few millennia, and so can be used to calibrate the seasons of unknown volcanic eruptions (Schüpbach et al., 2018). From here, I chose to use only Ca^{2+} to write a working code, which could then be repeated for the other species using a loop. Ca^{2+} concentrations were corrected for sea salt contribution to match the ice core data, using the following calculation (Fischer et al.,2007):

$nssCa^{2+} = Ca^{2+} - Na^{+} * (0.1)$

The phase of the frequency component equal to one is then calculated. This is then converted into the peak week of the Ca^{2+} concentration using the following calculation:

peak_week = ceil(52*phase/(2* π));

After applying the FFT to the signal, the component with a frequency of one was selected, and the other frequencies were then removed, and the signal was reconstructed. This removed all noise from the signal and showed a clear periodic trend of a single curve every year. This was then overlaid by the original signal, see Figure 4.

The peak week was then compared to a weekly averaged annual cycle to see if the peak week was consistent with the original data. This then can be used to calibrate and time the sulfate peak that represents eruptions of unknown volcanoes recorded in NEEM-S1-2011 ice core (Sigl et al.,2015).

3. Improvements

The main improvement made was in the code itself. At the start of this project, I had no experience with time series analysis (e.g., Fourier transforms) or coding experience. I studied the code written in Gore's (2021) project and online resources to gain knowledge in both areas. However, this took some time as the code was convoluted, not easy to understand, and had many areas that needed to be improved. I realised the importance of keeping code as clear and concise as possible, particularly when dealing with extensive data set analyses. I spent much of my time rewriting the code to make it more concise by using fewer tables and matrices to remove unnecessary lines of code. It made it easier to fix problems throughout by assigning suitable variable names, commenting on what I changed, and explaining what the code did. This also made the code more legible, allowing future work to be conducted with ease. I also learned the importance of version control, which is where I kept track and managed changes to the code over time. This allowed me to use the trial and error method to fix problems and revert to previous code versions if required. Furthermore, I added additional details such as Booleans, which allows the data to be manipulated with ease.

Another significant enhancement in Gore's (2021) project was the reduction of noise in the produced figures, which had previously obscured meaningful insights. Smoothing is a crucial aspect of data analysis as it enhances the visualization of patterns and trends. I introduced a smoothing window of 16, equivalent to a moving average of 4 weeks. This choice effectively reduced the noise in several species while preserving the periodicity and trend of the signal. Finally, the data was normalized to facilitate better comparison with other aerosol data.

4. Results

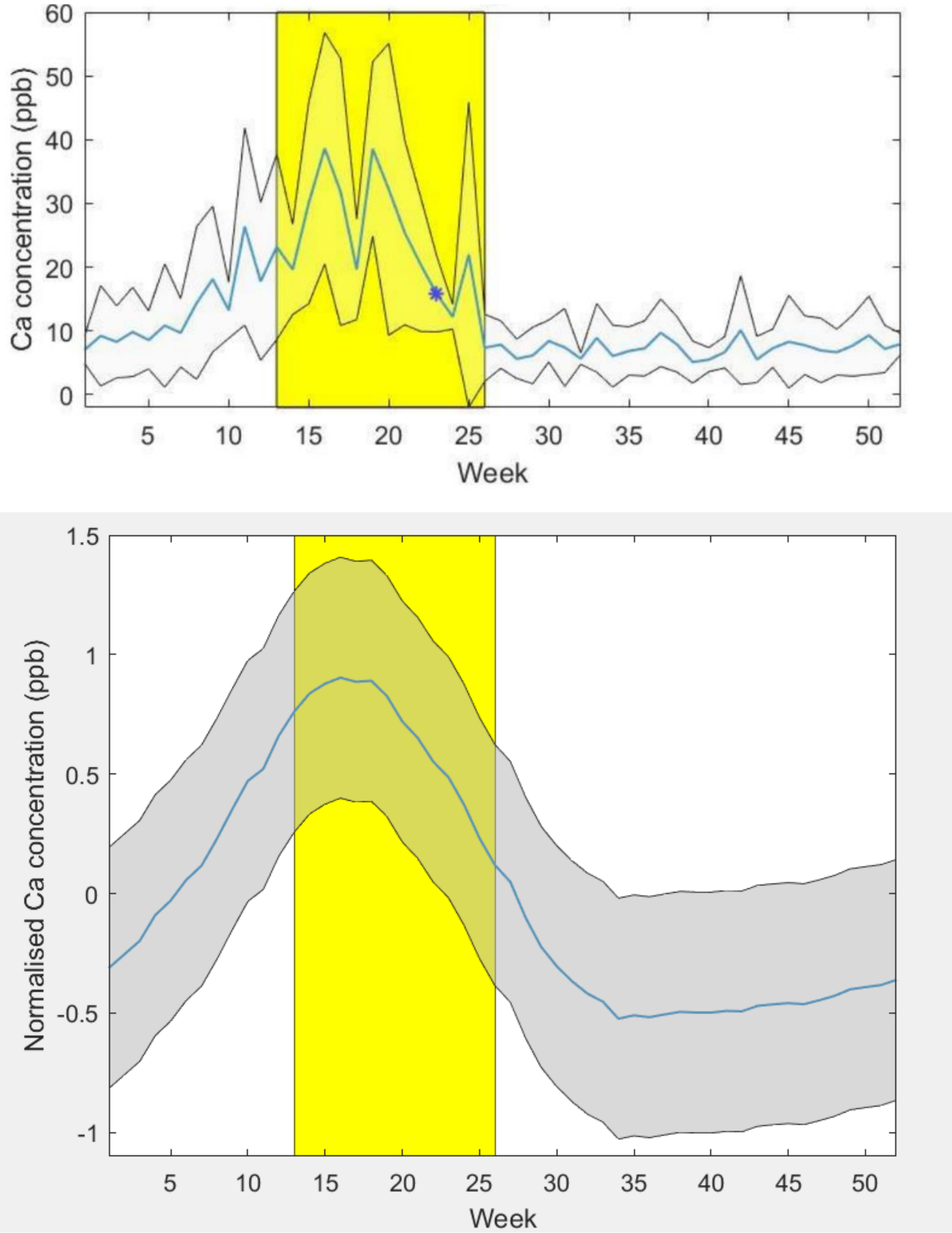

Figure 3

Both show annual cycle of Ca^{2+} concentrations in blue taken from snow samples at Summit. The standard deviation is shaded, and the yellow bar shows the timing of peak concentrations from the literature (Dibb et al, 2007; Whitlow et al,1992; Oyabu et al, 2016).

Top graph produced by Gore (2021), averaged by week across 2007 – 2011. Blue asterisk shows annual peak calculated with the FFT. Bottom, averaged by week, across 2007 – 2012 and smoothed with a moving average of 4 weeks.

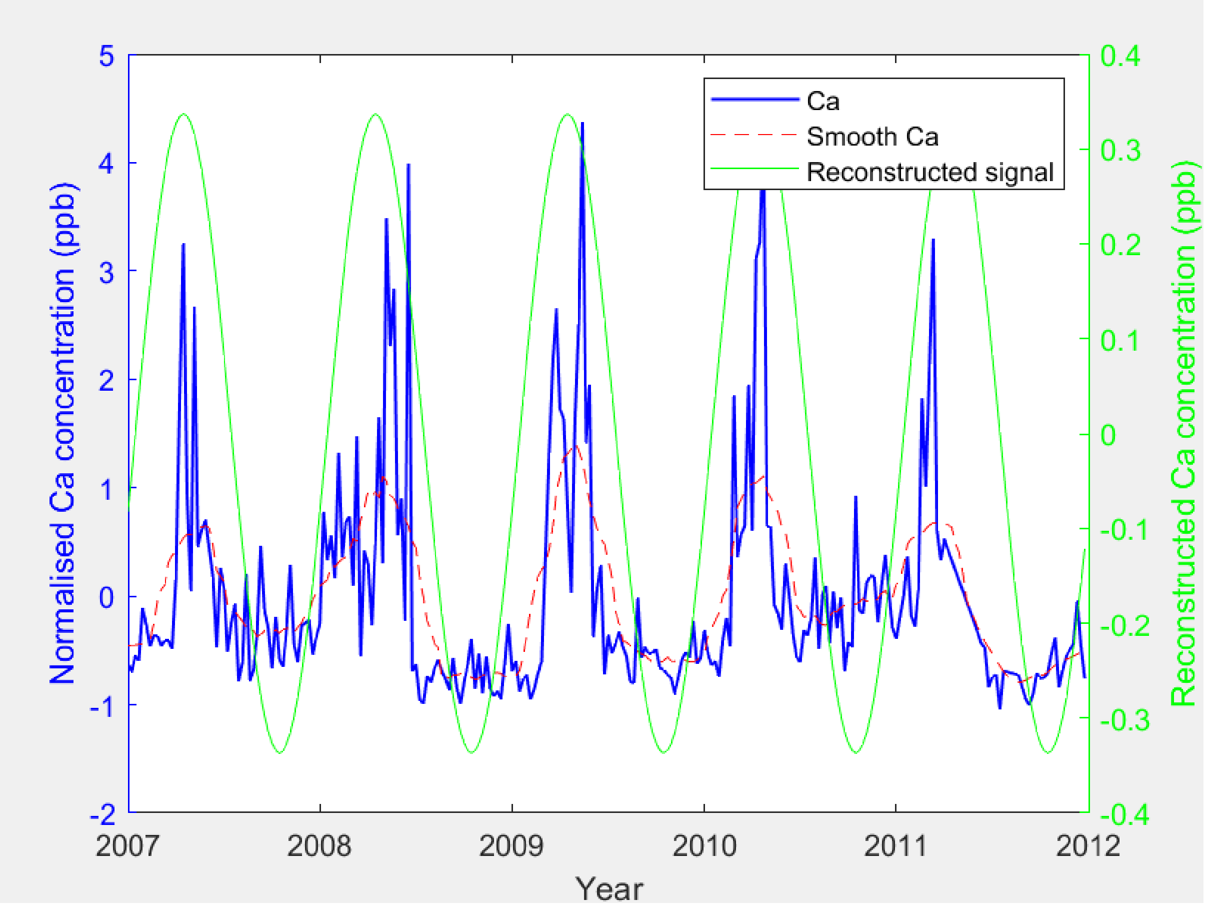

Figure 4

In blue, shows normalised timeseries of Ca^{2+} in surface snow at Summit over selected period with a sampling interval of a week or less 2005 - 2012.

In red, shows the same data as in blue but with a smoothing of a 4-week moving average applied. Follows the trend of the original data and removes much of the noise.

In green shows the results after applying a fast Fourier transform to the smoothed normalised data, then applying the inverse fast Fourier transform on component equal to frequency of 1 to reconstruct the signal. For visualisation this was scaled.

Figure 3 shows a clear improvement by introducing smoothing. In Gore's (2021) graph it is very difficult to distinguish the data trend and where the peak concentration is. My graph shows a clear peak around week 16-17. This is consistent with outside literature, shown in yellow, where the peak is found within. The blue asterisk shows the peak week calculated by the FFT which should be positioned at the top of the peak indicating the previous research was incorrect. In my code, the phase of the reconstructed signal in Figure 4 matches the phase of the other signals, suggesting that the fast Fourier transform was correct, but the phase calculation is not. As a result, this was removed from my graph and provides an opportunity for further investigation.

5. Discussion

The correct identification of phase and seasonal cycles of several species can be used to estimate the seasonality of known volcanic eruptions. Once these cycles are identified, the same method can be applied to estimate the seasonality of unknown eruptions using ion concentrations within an ice core. This approach can provide valuable insights into effective radiative forcing.

The seasonality of Ca^{2+} concentrations in Greenland ice cores is driven by varying air masses and dust sources. A spring maximum in Ca^{2+} is observed in snow samples from Southeast Dome and Summit, Greenland (Oyabu et al., 2016; Whitlow et al., 1992). However, this peak occurs later than in northern Greenland, where a March peak is noted at the NEEM site (Gfeller et al., 2014) and other locations (Kuramoto et al., 2011; Fischer, 2001). This variability reflects the relative influence of Pacific air masses in the north and long-range aerosol transport to the interior ice sheet, with Summit primarily receiving terrestrial dust from Asian deserts (Fischer, 2001; Whitlow et al., 1992).

The primary source of Ca^{2+} at Summit is terrestrial dust, particularly from the Takla Makan Desert in China, with potential contributions from an unidentified area (Bory et al., 2003; Gfeller et al., 2014). While Saharan dust is considered, its contribution is most likely limited due to the timing of dust emissions and transport patterns, which are dominated by westerlies from Europe and Asia and zonal winds from North America (Lupker et al., 2010; Kahl et al., 1997). It is noted that Western Sahara emissions in June and July may play a role (Laurent et al., 2008).

In this paper, I calculated a late April (week 16 or 17) peak in Ca^{2+}, consistent with the agreed spring peak in the scientific literature but with up to a 2-month discrepancy. This highlights an assumption within this methodology: that aerosols' seasonal cycles have remained the same over the past 2000 years. Due to the Asian deserts being the primary source of Ca^{2+}, there is evidence that variation in this ion concentration has been negligible over the last few thousand years (De Angelis et al., 1997; Schüpbach et al., 2018). However, this may not be true of other ions.

Secondly, using the FFT requires the input data to be sampled at regular intervals. This is rarely the case when working with climate data. When layers of snowfall, snow is converted to firn and then to ice as air is removed and pressure builds (Cuffey et al., 2010). In other words, the deeper the ice, the older the ice is. In this method, depth is used as a measure of time to date sulfur peaks within the NEEM ice core. However, a period of low snow accumulation would represent more years over a given depth than a period of high accumulation, or vice versa. To limit this inaccuracy, inter-annual snow accumulation rates could be considered in the future.

A further improvement could be to extract both the ice core and snow data from the same location. In this study, the NEEM ice core is 650km northwest of Summit, and therefore, deposition of aerosols in snow could vary seasonally between both locations. This means that peaks of aerosol concentration in the ice core may not be consistent with the calculated seasonality of the snow data. Furthermore, it is difficult to confirm that a peak in the ice core represents the ion concentration peak within that year. This is because, during the conversion of snow to ice, it may have been subject to post-depositional changes such as diffusion or a change in atmospheric circulation that would affect the transport of aerosols to Greenland (Fischer et al.,2001). The method could be further improved by repeating it over several ice core records as a sulfur record of an eruption has also been shown to vary spatially (Toohey and Sigl, 2017).

6. Conclusion

The work I completed in this project is an important step toward providing more accurate data for Paleoclimate Model Intercomparison Project simulations. The climatic response to volcanic eruptions is inherently linked to CO_2 levels, so this work is vital in understanding the climate system and future projections of climate change. I managed to identify and solve several problems with previous research and showed several avenues for the project to be continued and improved.

7. Acknowledgements

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