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Evaluating the Relationship Between Climate Change and Volcanism

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Abstract

Developing a comprehensive understanding of the interactions between the atmosphere and the geosphere is an ever-more pertinent issue as global average temperatures continue to rise. The possibility of more frequent volcanic eruptions and more therefore more frequent volcanic ash clouds raises potential concerns for the general public and the aviation industry. This review describes the major processes involved in short- and long-term volcano–climate interactions with a focus on Iceland and northern Europe, illustrating a complex interconnected system, wherein volcanoes directly affect the climate and climate change may indirectly affect volcanic systems. In this paper we examine both the effect of volcanic inputs into the atmosphere on climate conditions, in addition to the reverse relationship that is, how global temperature fluctuations may influence the occurrence of volcanic eruptions. Explosive volcanic eruptions can cause surface cooling on regional and global scales through stratospheric injection of aerosols and fine ash particles, as documented in many historic eruptions, such as the Pinatubo eruption in 1991. The atmospheric effects of large-magnitude explosive eruptions are more pronounced when the eruptions occur in the tropics due to increased aerosol dispersal and effects on the meridional temperature gradient. Additionally, on a multi-centennial scale, global temperature increase may affect the frequency of large-magnitude eruptions through deglaciation. Many conceptional models use the example of Iceland to suggest that post-glacial isostatic rebound will significantly increase decompression melting, and may already be increasing the amount of melt stored beneath Vatnajökull and several smaller Icelandic glaciers. Evidence for such a relationship existing in the past may be found in cryptotephra records from peat and lake sediments across northern Europe. At present, such records are incomplete, containing spatial gaps. As a significant increase in volcanic activity in Iceland would result in more frequent ash clouds over Europe, disrupting aviation and transport, developing an understanding of the relationship between the global climate and volcanism will greatly improve our ability to forecast and prepare for future events.

1 Introduction

It is already well established that various aspects of the Earth system, such as the atmosphere, geosphere and cryosphere, regularly interact through the exchange of materials and energy (Webster, 1994; Pielke et al, 1998). The global impact of large eruptions, such as the 1991 eruption of Mt. Pinatubo (Philippines, VEI 6) (McCormick et al, 1995), the 1815 eruption of Tambora (Indonesia, VEI 7) (Stothers, 1984), or the 1783-1784 eruption of Laki (Iceland, VEI 6) (Thordarson & Self, 2003), can be clearly seen in historical and environmental records (Robock, 2000). Injection of large quantities of volcanogenic material, such as fine tephra or volcanic gases (e.g. sulphur dioxide, carbon dioxide, hydrogen sulphide), into the stratosphere or troposphere can cause so-called ‘dust veil’ events (Lamb, 1970) with the potential to dramatically alter the Earth’s climate on a regional or global scale for short periods of time (typically on the scale of several years to decades). The year following the 1815 eruption of Mt Tambora, for example, is often referred to as the ‘Year without a summer’ global temperatures are estimated to have dropped by 0.4-0.7°C (Stothers, 1984), causing several weather anomalies (Raible et al, 2016), particularly across the northern hemisphere, and placing considerable strain on agriculture worldwide (Stothers, 1999).

The relationship between a changing global climate (specifically, one experiencing a warming period) and a potential increase in volcanic eruption frequency and/or intensity is relatively unexplored. McGuire (2010) suggests that periods of ‘exceptional climate change’ may be associated with increased levels of hazardous geological and geomorphological activity, based on early Holocene records and contemporary observations of glacier retreat, measurements of ground instability, and estimations of melt production beneath Iceland (Oerlemans et al, 1998; Óladttir et al, 2011; Magnusdottir et al, 2013). An increase in volcanic activity as a response to a warming climate as a result of isostatic adjustment has previously been suggested by multiple studies (Sull & McKenzie, 1996; Pagli & Sigmundsson, 2008; Watson, 2016). Such an escalation would have significant ramifications for local communities, and an increase in the frequency of ash clouds would have consequences for global aviation. As of 2014, approximately 100,000 commercial flights occur per day worldwide (Air Transport Action Group, 2016). Jet aircraft are extremely vulnerable to damage caused by interactions with even low concentrations of airborne ash particles, which may cause electronic failures, severe abrasion on the turbine fans (Grindle & Burcham Jr, 2003), and clogging of the engine through the melting and re-solidifying of ash particles (Dunn et al, 1993). Since 1976, approximately two severely damaging encounters between aircraft and volcanic ash clouds have occurred per year (Guffanti et al, 2010). Between 1944 and 2006, volcanic activity necessitated the closure of more than 100 airports in 28 countries on 171 separate occasions (Guffanti et al, 2009). The economic and social disruption caused by such events may be most clearly illustrated by reference to the relatively minor (VEI = 3) eruption of Eyjafjallajökull in Iceland in 2010, which resulted in the closure of a large region of airspace across the North Atlantic and Europe, causing the loss of approximately US $1.7 billion in revenue to various airlines in the space of a week (Mazzocchi et al, 2010). Volcanic ash can also pose a hazard to human health and the health of crops and livestock, particularly with regards to respiratory systems (Horwell & Baxter, 2006), even at relatively small concentrations (Horwell, 2007).

Regional climate change can also increase the likelihood of destructive non-eruptive events in volcanic regions, such as mass movements, including lahars (Thouret & Lavigne, 2000; Pierson et al, 2014). Increased rainfall has previously been a significant factor in several such disasters, including the 1998 collapse at Casita volcano in Nicaragua (Kerle et al, 2003; Scott et al, 2005), and the 2005 lahar at Toliman volcano in Guatemala, which destroyed the town of Panabaj and caused the deaths of more than 1,200 people (Luna, 2007). Changes to depositional and runoff channels following such events also has implications for hazard and risk estimation and models (Hayes et al, 2002).

The 2010 eruption of Eyjafjallajökull sharpened the focus of scientific research into the understanding and mitigation of volcanic ash hazards, particularly with regards to northern Europe and volcanism in Iceland. Strong interest from the media and government departments prompted rapid development of many ash modelling and monitoring techniques, most notably in the UK and Western Europe (Wilkins et al, 2016; Marenco et al, 2016). The unusual geochemical profile of Iceland (a result of its unique geological location above a mid-oceanic spreading ridge and a deep-seated mantle plume (hotspot); Oskarsson et al, 1985) and the relative wealth of data concerning eruptions in Iceland, in addition to the wide range of locations affected by Icelandic eruptions, make the region ideal for the study of evolving volcanic activity. Based largely on comparisons with known proximal deposits, Icelandic tephras have been identified in Scotland, England, Wales, Ireland, Germany, Sweden, Arctic Norway, Poland, Estonia and the Faroe Islands (Pilcher et al, 2005; Swindles et al, 2011; Lawson et al, 2012; Watson et al, 2017), forming a comprehensive record of Icelandic ash deposition across Europe. If the proposed relationship between periods of global warming and ‘flare-ups’ in volcanic activity can be shown to exist, the ramifications to modern society, particularly with regards to aviation and the agricultural industry, may be significant.

Understanding the intricacies of the links between the climate and volcanism requires investigation of both sides of the relationship. This review examines the established links between volcanism and subsequent surface cooling, in addition to assessing the potential for correlation between periods of climate warming and an increase in the frequency of volcanic eruptions, with a focus on Iceland and ash fallout across northern Europe. Iceland is frequently referred to as a case study, as much of the existing work pertinent to this review was conducted with a European focus.

2 Volcanic Forcing of the Climate

2.1 Short-term events

A link between large volcanic eruptions and variations in regional and global climate variability has been surmised to exist for at least several centuries. One of the earliest examples of scientific thought on the matter was published by Benjamin Franklin in 1784, following the catastrophic fissure eruption of Laki (also called Lakagigar) in Iceland in 1783 (Franklin, 1784). Franklin linked the observations of a 'haze' or 'mist' across much of Europe in the months following the onset of the Laki eruption to the significant temperature anomalies that characterised the winter of 1783. The mist Franklin referred to was caused by the release of approximately 122 megatons of sulphur dioxide (SO_2) from the Laki fissure, 95 Mt of which were injected into the lower stratosphere, ensuring widespread atmospheric dispersal (Thordarson & Self, 2003). Once injected into the atmosphere, SO_2 is chemically converted via the OH radical or via aqueous phase reactions to form aerosol mixtures of sulphuric acid (H_2SO_4). This increase in aerosol particle concentrations in the upper troposphere and lower stratosphere is thought to have caused significant cooling for a period of several months as a result of aerosol particles leading to enhanced scattering of incoming solar radiation back to space (Jacoby et al, 1999; Thordarson & Self, 2003; Oman et al, 2006; Schmidt, 2013). In the lower atmosphere, sulphur aerosols may also act as cloud condensation nuclei (Schmidt et al, 2011), furthering the surface cooling effect. There is evidence to suggest that this alteration to surface temperatures may have caused a weakening of the monsoon circulation in 1783 and 1784 through a reduction of the summer temperature contrast between the mid-latitudes and the equator, resulting in abnormally low precipitation and drought in Africa and India (Oman et al, 2006).

Several other large eruptions have had notable effects on the global climate. The eruptions of Krakatoa (Indonesia, August 1883), Agung (Indonesia, February 1963) and El Chichón (Mexico, March 1982) each had a short-term (several months to years) impact on surface temperatures, atmospheric temperatures, precipitation patterns and other aspects of the climate system (Self et al, 1981; Robock, 2000). In each case, the eruptions in question were explosive in nature, with a VEI (a quantitative measurement of the volume of material ejected during an eruption; Newhall & Self, 1982) of 5 or greater; however, some explosive eruptions of a similar magnitude, such as the eruption of Mt St Helens in 1980, have only negligible atmospheric effects (Robock & Mass, 1982). The determining factor in an eruption's climatic impact, therefore, is not the volume of material ejected from the vent, but whether a significant amount of that material reaches the stratosphere (Robock, 2000; Self, 2006). Larger dust and ash fragments typically have a residence time on the order of a few months in the atmosphere (Robock, 2000), and their effects disappear once the particles fall out and settle. By contrast, SO_2,has a lifetime of hours to days in the troposphere, though this may extend to approximately three weeks if released into the stratosphere (Schmidt & Robock, 2015).

The contribution of volcanic gases to climate forcing is much more significant than that of ash particles. The most abundant volcanic gases emitted during an eruption are those that are already at relatively high concentrations in our atmosphere (such as H_2O, N_2 and CO_2), and as such have only a minimal effect on atmospheric composition and climate; however, other volcanic emissions, such as sulphur compounds (e.g. SO_2, H_2S) have a much greater impact. These gases react with ambient hydroxyl radicals (OH•) and H_2O molecules to form sulphuric acid aerosols. If carried into the stratosphere by

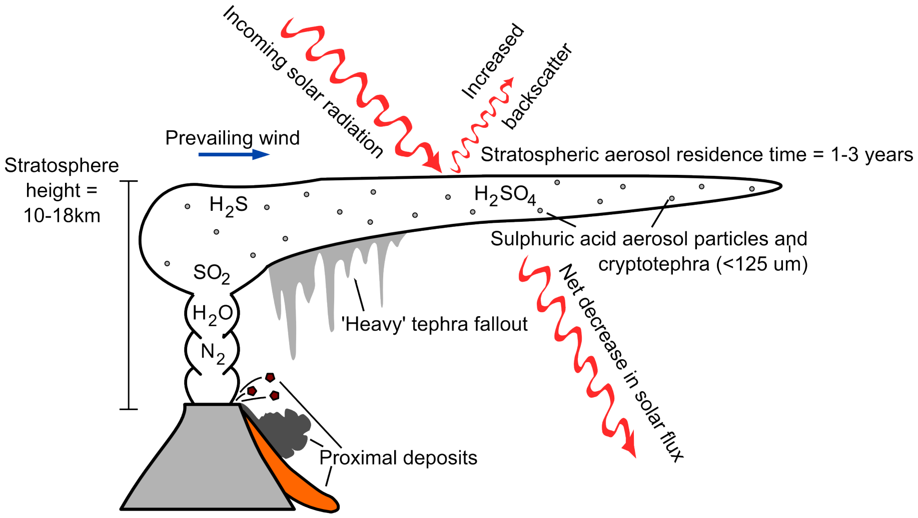

Figure 1: Schematic of volcanic inputs to the atmosphere. Most tephra particles will fall out within a time period of days to weeks, while lighter emissions may have a residence time of several months (in the case of tephra particles <125 μm in diameter) to years (stratospheric aerosols) (Robock, 2000). Chemical species with a naturally high atmospheric abundance (such as CO_2, H_2O and N_2) will have a much lesser effect than less abundant species, such as SO_2. Robock, 2000.

a volcanic column, these particles rapidly achieve global coverage, sometimes circulating the globe in as little as 3 weeks (Robock & Matson, 1983; Bluth et al, 1992; Self, 2006). The dominant effect of such an aerosol cloud is to greatly (albeit briefly) increase the planetary albedo by backscattering incoming solar radiation, resulting in net cooling at the surface. On a similar timescale, the aerosol particles also act as a catalyst for ozone depletion reactions which may result in anomalous regions of net surface warming, particularly in polar and mid-latitude regions (Solomon, 1999). In addition, the presence of an aerosol cloud can lead to stratospheric heating due to absorption of thermal infrared and near-infrared solar radiation. However, the global-mean net effect of such short-term aerosol releases is always one of mild surface cooling, typically less than 1°C lower than ambient conditions (Rampino et al, 1988; Santer et al, 2016).

The geographic location of the initial eruption also plays a factor in determining an eruption's atmospheric impact (Robock, 2000; Toohey et al, 2011). Large-scale patterns of air circulation enable a more global dispersal of aerosols from tropical eruptions, whereas airborne material from high-latitude eruptions is more likely to remain in the hemisphere into which it was injected (Oman et al, 2006). In addition, stratospheric heating can increase the meridional temperature gradient, strengthening the polar vortex and causing alterations in stratospheric circulation (Robock & Mao, 1992; Kirchner et al, 1995; Fischer et al, 2007). However, the complexities in the response of the atmosphere to the asymmetric cooling effects produced by volcanic eruptions are as yet poorly understood. The temperature anomalies that occur following volcanic aerosol injection are far from homogeneous (Haywood et al, 2013; Svensson et al, 2013; Ridley et al, 2015). Baldini et al (2015) suggest that high-latitude eruptions in either hemisphere may also have significant atmospheric effects by causing cooling in one hemisphere relative to the other, forcing migration of the Intertropical Convergence Zone (ITCZ). Current southward migration of the ITCZ in response to anthropogenic aerosol emissions is thought to be a major cause of frequent droughts experienced by the Sahel region of Africa (Hwang et al, 2013), and is a major control of air currents and associated precipitation in equatorial and low-latitude areas (Huang et al, 2001; Ridley et al, 2015).

2.2 Decadal to century-scale effects

In all observed incidences, volcanic aerosols are typically short-lived, with the result that their effects are generally only experienced on an interannual scale (Robock, 2000). However, there are suggestions that explosive volcanic eruptions may also have longer-lasting 'knock-on' effects. One such proposal is that large tropical eruptions may trigger the onset of certain ENSO (El Niño Southern Oscillation) states, and affect the magnitude of subsequent El Niño events, though the topic remains controversial (Self et al, 1997; Maher et al, 2015). Multiple attempts have been made to establish a causative link between eruption events and the onset of El Niño cycles through analysis of proxy data (Adams et al, 2003) or numerical modelling (Meehl & Washington, 1996; Boer et al, 2000); however, while the analyses do suggest the possibility of a connection between explosive volcanism and ENSO phenomena, discrepancies in event timings and the influence of other factors on the likelihood of ENSO variations continue to cause uncertainty on the subject (Self et al, 1997; Emile-Geay et al, 2008).

Baldini et al (2015) used ice core, volcanological and speleothem data to suggest that unusually large volcanic events (i.e. VEI 5 or greater) might be at least partially responsible for abrupt millennial-scale shifts in the global climate characterised by rapid periods of warming in Greenland and apparently synchronous cooling in Antarctica, termed Dansgaard-Oeschger (DO) events. DO events are typically characterised by extremely rapid warming over a period of 20-50 years, followed by a period of relatively warmer climate which may last several centuries to millennia (Mogensen, 2009). The timing of DO events is largely constrained by the examination of oxygen isotopes from Greenland ice cores (Dansgaard et al, 1993), and multiple possible explanations for their occurrence have been suggested, including solar forcing, meltwater injections and oscillations in ocean-atmosphere interactions. Baldini et al (2015) argue that following an exceptionally large eruption, such as the supereruption of Lake Toba approximately at 75 kya, the ensuing atmospheric temperature asymmetry could have caused sufficient disruption to global circulation patterns to initiate a series of positive feedbacks, including sea ice expansion, increased surface albedo, and weakening of the Atlantic meridional overturning circulation (AMOC). Similar feedback loops thought to be triggered by volcanic eruptions have been implicated as factors in other Quaternary cooling events (Stuiver et al, 1995; Baldini et al, 2015). Miller et al (2012) also suggest that the onset of the Little Ice Age (approximately 1300 AD) may have been triggered by the occurrence of four sulphate-heavy eruptions in quick succession, based on measurements of stratospheric aerosol loadings by Gao et al (2008).

On a longer time scale, there is substantial evidence that the emplacement of unusually large igneous provinces (i.e. flood basalt volcanism) may be linked to periods of long-term global climate change. Most of these eruptions are estimated to have occurred on a timescale of approximately 1 Myr (Hofmann et al, 1997), and are frequently linked to sudden shifts in the global climate, as well as to mass extinction events (McLean, 1985; Campbell et al, 1992; Courtillot & Renne, 2003; Bond & Wignall, 2014). During the formation of the Deccan Traps, for example, at the Cretaceous/Tertiary boundary at approximately 65 Ma, it is thought that around 5 x 10^{17} moles of CO_2 may have been released into the atmosphere at a rate of up to 9.6 x 10^{11} moles CO_2 per year (McLean, 1985). It has been estimated that the same eruption could also have released 10,000 Tg of SO_2 over a decade (Self et al, 2006). In addition, it is thought that flood basalt events (which may attain cumulative volumes of several thousand cubic kilometres; Coffin & Eldholm, 1994) may also cause significant contact metamorphism of overlying and underlying sedimentary rocks (such as carbonates, coal or shales), generating further quantities of greenhouse gases (Ganino & Arndt, 2009), particularly CO_2. Estimating the climatic impact of flood basalt events is greatly complicated by the apparently contradictory effects of the two major gases released. While volcanic SO_2 generally has a cooling effect when converted to sulphuric acid aerosol in the stratosphere, as discussed above, CO_2 is a greenhouse gas, and in high enough atmospheric concentrations causes significant surface warming. However, whether sufficient concentrations of CO_2 could have been achieved during the emplacement of large igneous provinces remains disputed; while some models predict a net greenhouse effect (Caldiera & Rampino, 1990; Dessert et al, 2001), others argue that the volumes of CO_2 released would have been small in comparison to the natural atmospheric reservoir, particularly in ambient greenhouse conditions, such as those of the late Cretaceous (Self et al, 2006). Thus, in most cases the controlling factor in terms of atmospheric change is likely to be the quantity of SO_2 emissions, making the net effect likely to be one of cooling (Schmidt et al, 2016).

Flood basalt volcanism has also been suggested as a contributing factor in the mid-Jurassic Pliensbachian-Toarcian mass extinction event, most notable in the depletion of bivalves and other marine invertebrate species as a result of an oceanic anoxic event (OAE)(Aberhan & Fürsich, 2000). Pálfy and Smith (2000) link the event to the synchronous Karoo-Ferrar flood volcanism, which occurred in southern Gondwana (modern southern Africa/Antarctica) 184 - 179 Ma (Duncan et al, 1997). Based on U-Pb ages for the flows within the Karoo Traps and ocean sediments from the Toarcian OAE, Pálfy and Smith (2000) suggest that heightened extinction rates were sustained for approximately 4 Ma, reaching a peak at 183 Ma. This correlates with the peak of flood volcanism, in which approximately 1 x 10^6 km^3 of material is believed to have been extruded over the course of 1 Myr (Duncan et al, 1997; Riley et al, 2006). Though the topic is still debated (Svenson et al, 2007; Ikeda & Hori, 2014), the OAE is thought to have been at least partially triggered by volcanic CO_2 release, coupled with multiple synchronous events, likely unrelated to volcanic activity, most notably massive methane hydrate dissociation (Hesselbo et al, 2000). The suggested contribution of multiple secondary factors to the extinction event, such as enhanced global mercury deposition (Percival et al, 2015) and a proliferation of endemic species during the late Pliensbachian (Aberhan & Fürsich, 2000), ties into the argument presented by Wignall (2005) - that while volcanic CO_2 emissions may initiate major perturbations to the global carbon cycle, other factors occurring either as a result of or unrelated to the initial eruption are likely to be necessary to cause major climatic change. Whether the emplacement of large igneous provinces may be ultimately responsible for, or merely a contributing factor to any subsequent mass extinction events remains to be determined. Nevertheless, it is clear that wide-scale interplay between the Earth's atmosphere and geosphere currently exists, and has existed in the past on a range of scales, and will continue to do so for the foreseeable future.

3 The Potential for a Volcanic Response to Climate Change

3.1 Proposed mechanisms

3.1.1 Climate, glacier response, and the Icelandic Low

The majority of studies attempting to model the effect of a warming climate on volcanic eruption frequency are performed in the context of the Icelandic glaciers and volcanoes, though the same link may potentially exist in other locations (see section 5.2). The relatively rapid response of the Icelandic glaciers to fluctuations in oceanic currents is well documented (Bond et al, 1997; Rahmstorf, 2002; Björnsson & Pálsson, 2008). Numerous palaeoclimate proxies indicate multiple periods of oceanic cooling in the North Atlantic over the past 10 ka BP (Watson et al, 2016b). In particular, decreased sediment productivity across multiple Icelandic lakes suggests a significant cooling event at approximately 6.4 ka BP (Geirsdöttir et al, 2013), and geochemical analysis of a Greenland ice core by Mayewski et al (1997) shows fluctuations in the concentration of sodium (Na+), which may indicate a deepening of the Icelandic Low atmospheric system between 3.5-2.5 ka BP. The strengthening of regional wind speeds that would occur following the onset of a deeper Icelandic Low would result in enhanced transportation of sea salts, resulting in greater concentrations of Na+ present in the ice core (Mayewski et al, 1997). However, ice core records of the Holocene indicate that variations in Earth's climate were of a lower amplitude than those seen during the Pleistocene, suggesting that the climate has been more stable in the past 10,000 years than at any point in the last 100,000 (O'Brien et al, 1995; Mayewski et al, 2004).

Evidence of glacial advance in the south, centre and north of Iceland coincides with the climatic cooling events described above (Gudmundsson, 1997; Kirkbride & Dugmore, 2001; Kirkbride & Dugmore, 2006). Kirkbride and Dugmore (2006) suggest that, as smaller glaciers are more susceptible to the impacts of climatic forcing, they may account for the vast majority of short-term glacial expansion effects. Larger ice sheets, such as Vatnajökull, the largest Icelandic glacier, have a longer response time when compared with smaller glaciers (Oerlemans & Fortuin, 1998) - the total lag time between significant climatic changes and glacial response typically ranges between 10 and 1000 years (Jóhannesson, 1985). A mass balance study of Icelandic glaciers over the 20th century by Björnsson et al (2013) found that regional temperature fluctations correlated strongly with the rates of glacier retreat or growth. Between 1995 and 2010, the average Icelandic temperature increased by approximately 1˚C (3 to 4 times higher than the hemispheric average; Jones et al, 2012), coinciding with a loss of 3.7% ice mass at Vatnajökull and an 11% loss at Hofsjökull (Björnsson et al, 2013). The authors attribute these changes to longer melting seasons, thinner snow accumulation resulting in lower glacier albedo, and a greater ratio of precipitation falling as rain rather than snow. Oerlemans & Fortuin (1992) noted that the greatest factor in determining a glaciers responsiveness to external forcing is the wetness of the climate, and several recent studies concur that Icelands setting as an island contributes to the relatively rapid response of its glaciers and ice sheets to climate change (Björnsson & Pálsson, 2008; Chandler et al, 2016a, 2016b).

Possibly the most important factor in understanding and modelling the response of the cryosphere to a warming climate, particularly in northern Europe, is observing alterations to global thermohaline circulation patterns. The North Atlantic Deep Water (NADW) is a key component of this system. Benthic oxygen isotope, cadmium and ^{13}C data from sediment cores imply that a relative shallowing of the current coincides with warming phases, while ebbs may be linked to rapid cooling, such as the Younger Dryas (12.9 11.7 ka BP) (Boyle & Keigwin, 1987). Changes to thermohaline circulation patterns have been identified as *'a major factor in forcing the climate signal and in amplifying it'* (Bond et al, 1997), and it is thought that even small perturbations to the system may have had the potential to cause regional temperature changes on the order of several degrees during the Late Glacial and Early Holocene periods (Rahmstorf, 1996). On a regional scale, many factors related to a warming climate have been identified as major drivers of terrestrial glacier retreat, though the components with the greatest impact are likely to be increased atmospheric temperatures, increased precipitation, and the growth of supraglacial lakes (Reynolds, 2000; Björnsson & Pálsson, 2008).

3.1.2 The unloading effect

The 'unloading effect' refers to crustal deformation (specifically uplift) as a response to deglaciation. Isostatic rebound occurs after a load (such as a large glacier) is removed from the lithosphere. This has been directly or indirectly observed in Iceland (Sigmundsson, 1991; Sigvaldason, 1992), northern Europe (Lambeck, Smither & Johnston, 1998) and North America (James & Morgan, 1990). It is also generally accepted that rapid decreases in pressure (rapid on a geological timescale - on the order of at least a few centuries) cause an increase in the extent of decompression melting of the mantle (Asimow et al, 1995), suggesting that an association between the two factors may be plausible.

The divergent plate boundary combined with hotspot activity beneath Iceland is already the source of large quantities of decompression melting (Slater

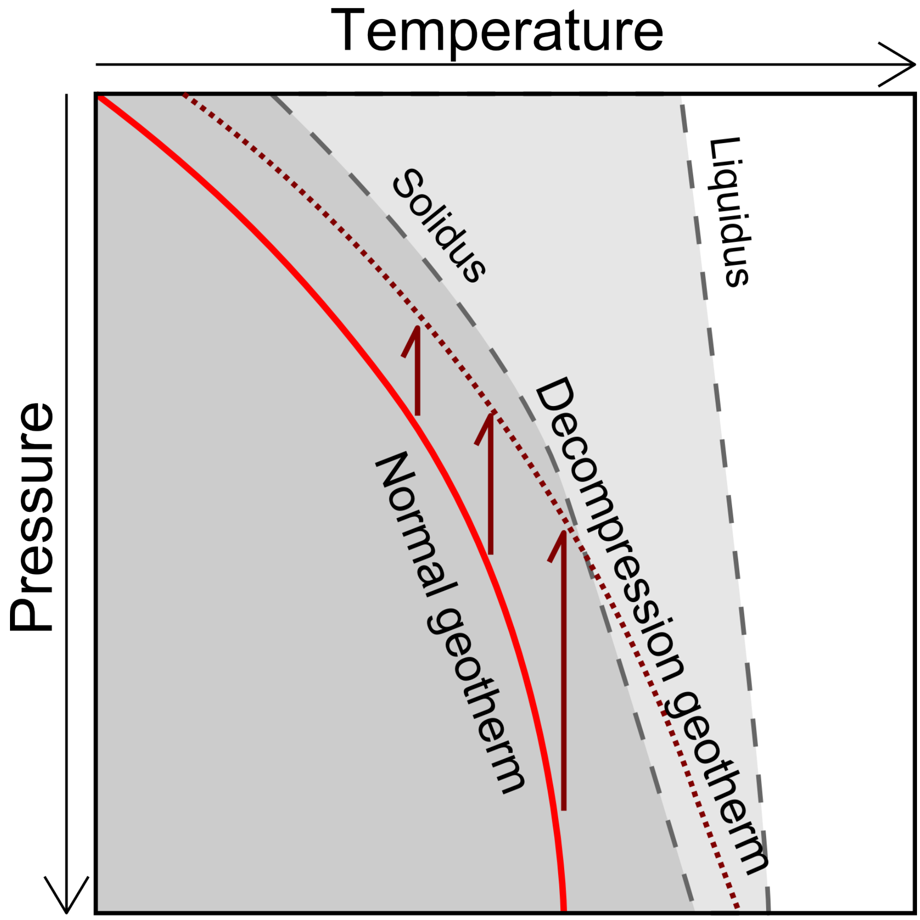

Figure 2: Example pressure-temperature diagram illustrating how decompression may alter the geotherm of a magma body, allowing for the production of greater quantities of partial melt. Rapid upwelling of the mantle causes a sudden decrease in pressure, altering the geothermal gradient to such a point that it intersects the solidus, allowing melting to begin.

et al, 2001). However, Jull and McKenzie (1996) estimate that the removal of 2 km of ice would increase the melt fraction by approximately 0.2%, though the increase in melt generation as a response to unloading is non-linear. Schmidt et al (2013) go further, suggesting that the Icelandic uplift due to glacial isostatic adjustments (currently estimated at 25-29 mm/yr; Auriac et al, 2013) has resulted in an annual melt production increase of 100-135% since 1890. Much of this new magma is believed to be located beneath central Iceland, with approximately 20% hosted by the mantle beneath Vatnajökull, a region containing some of the island's most productive volcanic centres, such as Grímsvötn (Schmidt et al, 2013). Even on a smaller scale, minor alterations in the crustal stress fields surrounding shallow magma storage regions may have a significant impact on the likelihood of an eruption, particularly at volcanic centres with glacial caps (Albino et al, 2010). Watson et al (2016c) draws a correlation between the depth of the Icelandic Low (as determined through analysis of the GISP2 Na+ record (Mayewski et al, 1997)) and the frequency of explosive Icelandic eruptions over the last 7,000 years. Their findings indicate that in both instances of Na+ increase, volcanic activity on Iceland decreased significantly. There was a lag of approximately 650 years between climate alteration and geodetic response, which the authors attribute to the delay in the glacial reaction, and the time taken for new excess magma due to adiabatic melt to reach the surface.

3.2 Evidence for a volcanic response

3.2.1 Tephrochronology and 'cryptotephra'

Many of the current research efforts investigating a geospheric response to global warming utilise the rapidly developing field of tephrochronology in an attempt to reconstruct the relative frequency of past volcanic events (Dugmore, 1989; Hall & Pilcher, 2002; Davies, 2015). 'Cryptotephra' refers to particles of volcanic ash which are not visible to the naked eye, typically being 125 μm (Lane et al, 2014; Stevenson et al, 2015; Watson et al, 2016b). These particles are often concentrated into layers within well-preserved sediment, such as in lake beds or peat bogs (Hall & Pilcher, 2002), and can provide useful isochrons across multiple sites within an area (Lane et al, 2014; Watson et al, 2016a).

Previously, cryptotephra has been used primarily as a dating and correlation tool in geological and archaeological fields (Balascio et al, 2011; Lowe, 2011; Schmid et al, 2017). However, more recent studies have focused on volcanological applications, such as the reconstruction of undocumented eruptions (Sun et al, 2016; Martin-Jones et al, 2017; Watson et al, 2016b), and – on a wider scale – the analysis of past patterns of volcanic eruptions (Connor et al, 2001), and the transportation of ash particles (Watson et al, 2016b). Watson et al (2017) use cryptotephra layers acquired from peat and lake sediments to estimate the recurrence interval of Icelandic ashfall across Northern Europe. Using data representing the past 1000 years, the study estimates an average return interval of approximately 44 years (a 20% chance of occurrence within a given 10-year period), based on samples from Germany, Scandinavia, Ireland, Great Britain, Poland and the Faroe islands (Swindles et al, 2011). Swindles et al (2011) report an apparent increase in the number of ash-fall events affecting Europe over the past 1,500 years; however, it is unclear whether this is due to a true increase in volcanic activity during this period, or is an artefact of sampling intensity and improved methodology. It is also possible that more recent events are preferentially preserved in the geological record, and as such assessments of ashfall frequency based solely on tephra will always represent a minimum estimate (Watson et al, 2017).

The assignment of a given tephra or cryptotephra horizon to a particular eruption relies heavily on geochemical analysis of glass shards, in combination with other physical and historical constraints, such as ^{14}C dating, wiggle-match dating techniques and ice core chronologies, where applicable (Lowe, 2011; Swindles et al, 2011; Lowe et al, 2013; Ramsey et al, 2015; Alloway et al, 2017). Various uncertainties still remain in the use of the technique, and the geochemical analysis of individual shards is not yet routine in tephra studies. However, by dating individual tephra layers, it is possible to estimate the relative frequency of volcanic events in a given area. In recent years, collaborative database resources such as Tephrabase (www.tephrabase.org) have emerged in an effort to catalogue the glass shard geochemistry of historic eruptions, greatly smoothing the process of cryptotephra identification.

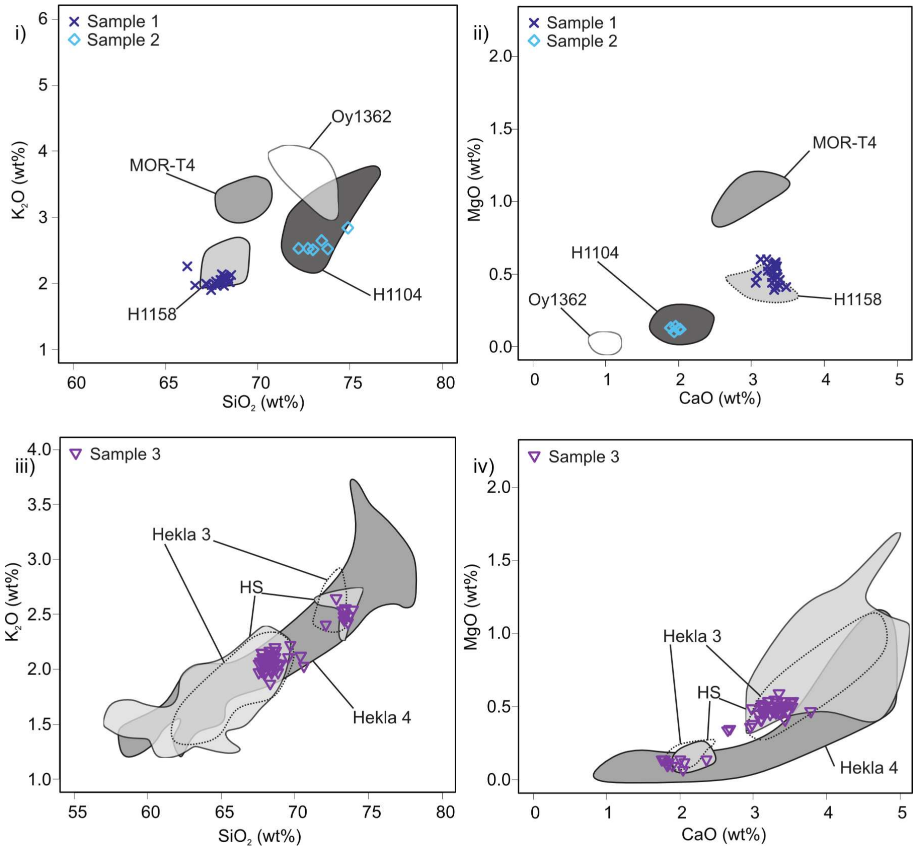

Figure 3: Bi-plot geochemical analyses of three tephra samples collected from a peat bog in the Shetland Isles (Swindles, unpublished data), compared with the known geochemical signatures of seven historic Icelandic eruptions (grey polygons)(Newton et al, 2007). This example illustrates how cryptotephra which falls into a particular geochemical 'envelope' may be ascribed to a single eruption. In this case, sample one (blue 'x's; seen in plots (i) and (ii)) most closely matches the H1158 eruption (Hekla), sample 2 (cyan diamonds; plots (i) and (ii)) is most similar to H1104, and sample 3 (purple triangles; plots (iii) and (iv)) is similar to the Selsund (HS) 1800 - 1750 cal. BC eruption.

Analysis of cryptotephra layers can also provide other valuable insights into the processes and characteristics of prior eruptions. For example, the shape and vesicularity of ash shards may provide information about the conditions under which they were formed and transported (Heiken, 1974; Colucci et al, 2013).

It is well recognised that the dominant shape of tephra shards (particularly regarding the ratio of the longest to the shortest axis) has a significant effect on the distance those shards may be transported before settling (Wilson & Huang, 1979; Folch, 2012). The concentrations of shards (also known as 'tephra loading') may be affected by the distance of the site from the source volcano, or by ambient conditions at the time of emplacement (Langdon and Barber, 2004; Rea et al, 2012).

3.2.2 Modelling efforts

Many studies within the past two decades have attempted to evaluate the effect of ice loading on volcanic activity, both via numerical modelling or through evaluation of historical evidence. Jull & McKenzie (1996) endeavoured to model the effect mathematically, utilising data obtained from tephrochronology of the Dyngjufjöll region of North Iceland. Their results indicated that the removal of 2 km of ice would have an effect approximately equivalent to a 0.6 km upwards shift in the melting column (although it should be noted that the thickest glacier currently in existence - the Taku glacier in Alaska - is less than 1.5 km thick (Robert & Hermans, 2000)). Jull & McKenzie go on to estimate that total deglaciation of Iceland would increase overall melt production rates by a factor of 30 over a period of 1000 years.

More recent studies have produced more conservative results. Pagli & Sigmundsson (2008) modelled the maintenance of isostatic equilibrium within the lithosphere using the assumption of an elastic plate overlying an isotropic, incompressible, viscoelastic half-space. Adopting contemporary measurements of ice loss and uplift beneath Vatnajökull (Pagli et al, 2007), the study found that, while present rates of ice thinning increase the volume of magma by approximately 0.014 km^3/yr, the effects are confined within existing regions of volcanic activity. Their model also concluded that, although the rates of vertical uplift were likely to be greatest towards the centre of the ice cap, volcanoes peripheral to the glacier, such as Kverkfjöll or Bárdarbunga, experienced greater radial glacio-isostatic stresses and were more likely to alter their behaviour than those in a central location, such as Grímsvötn. Additionally, the existing tectonic stresses in the region (the western edge of Vatnajökull is situated above the axis of Icelands Eastern Rift) play a role in determining the exact response of the volcanic systems (Pagli & Sigmundsson, 2008). However, while stating that the effects of increased melt production might be offset by intrusive processes and glacio-isostatic stresses, the study ultimately asserts that the likelihood of a large volcanic eruption within the region is increased by the retreat of the overlying glacier. The results of Jellinek et al (2004), Huybers & Langmuir (2009), Albino et al (2010) and Schmidt et al (2013) echo this inference.

4 Areas of Uncertainty

4.1 Gaps in the tephra record

The analysis of tephra and cryptotephra remains a relatively recent field of study. The current tephra record for Icelandic eruptions contains many spatial gaps, introducing an element of uncertainty into the analyses of fallout areas and eruption frequencies. While it is possible that these gaps represent regions of minimal fallout (i.e. locations that may not commonly experience ashfall due to prevailing meteorological conditions), it is also highly likely that they are an artefact of research intensity (Watson, 2016a). Swindles et al (2011) present a database of Holocene tephra records across northern Europe, noting that the abundance of data recorded in Ireland and Scandinavia is much greater than in other regions . Lawson et al (2012) also provides an analysis of 22 Holocene tephra deposits found in north western Europe, again noting the geographical bias resulting in the underrepresentation of certain continental areas (such as Spain, southern Germany, Belgium and the Netherlands) while also indicating spatial gaps in northern Scandinavia and the western Baltic (Lawson et al, 2012), though recent efforts have focused on addressing this issue (Watson et al, 2016b). Additionally, there is a question of glass shard preservation and reworking following deposition - meteorological conditions, vegetation and (more recently) anthropogenic factors may affect the likelihood of ash fallout preservation (Watson, 2016c). The tephra chemistry may also play a role in preservation - basaltic glass is more readily dissolved by acidic depositional environments than rhyolitic, resulting in the preferential preservation of silicic eruptions (Lawson et al, 2012). To enable a complete understanding of the processes governing the emplacement of these deposits, it is imperative to establish whether these omissions indicate a true absence of tephra horizons in the locations in question, or if they are simply an artefact of sampling bias.

4.2 Volcanic and tectonic processes

Unfortunately, as our understanding of volcanic processes remains incomplete, so too does our ability to fully predict the response of volcanic systems to external stimuli. Taking Iceland as an example once again, there remains considerable uncertainty over the variability of rifting across the region (Saemundsson, 1974; Metzger & Jónsson, 2014), and whether large scale changes in the rate and geographical trends of the main axis of rifting might be linked to the presence of a deep mantle plume or ‘hotspot’ (Ofeigsson et al, 2013; Karson, 2016). The present-day rifting zone in eastern Iceland is thought to have become active at around 4-3 Ma (Saemundsson, 1974; Sinton et al, 2005), and to have remained approximately static since that time, with the exception of a brief eastwards shift of the Spar fracture zone roughly 3 Ma (Meyer et al, 1972). It is thought that this section of the rifting zone may have migrated incrementally eastwards in order to accommodate westward drift of the lithospheric plates over a stationary plume. Periods of increase in rifting activity (such as the major rifting episodes known to have occurred at 12 ka, 11 ka, 10 ka and 3 ka) correspond with periods of enhanced eruption rates, particularly in Iceland’s Northern and Western volcanic zones (Magnusdottir et al, 2013). Therefore, any major deviations in underlying tectonic and volcanic processes must be taken into account when attempting to assess the impact of deglaciation. Changes in the rate of rifting are likely to cause centennial variations in eruption frequency (Larsen et al, 1998), while fluctuations in mantle plume activity may cause multi-millennial changes (Óladottir et al, 2011). However, Watson (2016c) argues that such pulses are unlikely to simultaneously affect multiple sites at varying distances from the central spreading ridge in precisely the same manner, hypothetically allowing the signal produced by ice loading to be separated from other factors.

Another issue raised in opposition to the hypothesis that the unloading effect might increase volcanic eruption frequency is that the pressure changes associated with ice retreat may also increase the capacity of the crust to capture melt. Hooper et al (2011) used a numerical model based on radar and GPS measurements of the Kverkfjöll volcanic system to show how relaxation of the stress fields surrounding the volcano might support magmatic intrusion rather than eruption of magma. However, their findings also indicated that dyke orientation is a major factor in determining crustal storage capacity, and that changes in crustal loading alter the conditions required for dyke initiation (Albino et al, 2010). The overall conclusion reached by Hooper et al (2011) was that, while deglaciation might increase magmatic storage capacity in the short term, ultimately increased mantle melting would become the dominant factor.

5 The Potential for Future Work

5.1 A more comprehensive record of past volcanism

While evidence of past volcanic eruptions are typically well-preserved in both the proximal record (i.e. in visible tephra layers and flow deposits), and often also in the distal record as cryptotephra, in many areas the dataset of past events may be considered to be incomplete. Though many sources suggest an apparent increase in the frequency of large volcanic events in Iceland over the past 2 ka (Zielinski et al, 2002; Óladóttir et al, 2011), it is highly possible that inference is largely a result of the preferential preservation of younger ash layers (Watson, 2016c), an increase in the number of studies, and recent improvements in research techniques, such as advances in geochemical analysis. A thorough campaign of investigation, centred particularly around the examination of the distal record and addressing the identified spatial gaps (as previously discussed), is necessary to confidently evaluate the past levels of volcanic activity, both in Iceland and in other locations. Efforts to this end are currently ongoing in northwestern and continental Europe (Swindles et al, 2011; Lawson et al, 2012; Watson et al, 2016b) and more recently in North America and Greenland (Pyne-O'Donnell et al, 2012; Mackay et al, 2016), but there is also great potential for such work to be conducted in other parts of the world, as evidenced by the discovery of Holocene cryptotephra in Peru (attributed to the Ecuadorian Eastern Cordillera) (Watson et al, 2015). A recent intensive study focusing on Japan (Kiyosugi et al, 2015) found that as much as 89% of VEI 4 events over the past 100 ka may be missing from the geological record, and the authors go on to estimate that under-recording of events may be 7.9-8.7 times higher in the global dataset.

However, the effect of deglaciation on volcanism in the near future is likely to be more substantial in the northern hemisphere, as glacier and ice sheet coverage in that hemisphere is more widespread. Additionally, while the focus has hitherto been on explosive events (as these are more likely to leave distal deposits in the geological record; Swindles et al, 2011), there is significant evidence that the greatest quantities of volcanic sulphate emissions may occur during large effusive eruptions (Krueger et al, 1996; Schmidt, 2013). Examining the aerosol contents and acidity profiles of ice cores, typically from Greenland and Antarctica, can provide insights into the timing and subsequent climatic effects of volcanic eruptions (Robock & Free, 1995; Cole-Dai, 2010). Sigl et al (2015) use tephra analysis (among other methods) to constrain the dates of several sulphate peaks in the ice core record. Though explosive eruptions are more likely to deliver ash across multiple atmospheric layers and therefore present a greater danger to aviation, it may be of interest from a climatological perspective to compare the levels of climate forcing resulting from different eruption regimes and compositions.

5.2 Quantifying the unloading effect

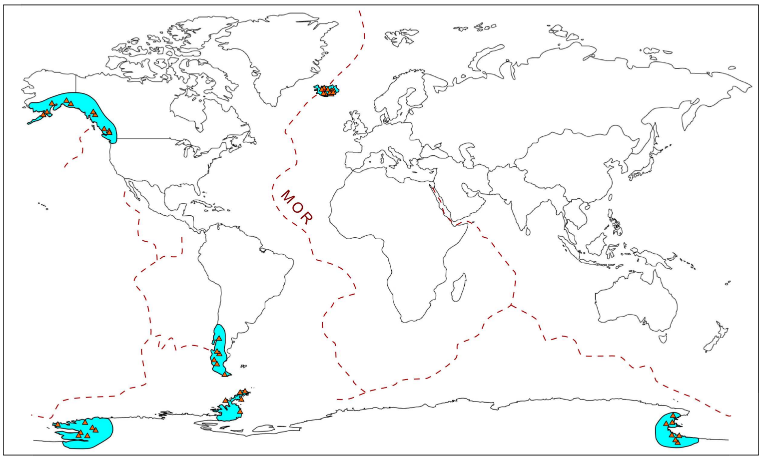

Figure 4: Multiple areas worldwide meet the following criteria: That they have 1. displayed significant volcanic activity within the past 11,500 years, and 2. currently have one or more large glaciers or ice sheets. These areas are typically within polar/sub-polar latitudes, and are marked in blue. Volcanoes active within the past 5,000 years are indicated with red triangles. Mid-oceanic ridges are marked with red dotted lines. The most significant identified regions in which the unloading effect may exert an influence are Alaska/western Canada, southern Chile/Argentina, Iceland, and several regions in coastal Antarctica, including the Antarctic Peninsula and the perimeter of the Ross Ice Shelf.

The issue of geographic sampling bias is also present in models of future changes related to glaciation. Most attempts to model a volcanic response to ice load variations focus on examples from Iceland (Sigmundsson, 1991; Sigvaldason, 1992; Pagli & Sigmundsson, 2008; Sigmundsson et al, 2010). A more global view of this effect may offer new insights, and may provide important data to advise policy beyond Europe's airspace. Through combining Smithsonian Global Volcanism Database and the Randolph Glacier Inventory (GLIMS, 2017; see figure 4), it is possible to identify several areas worldwide in which:

1. Significant volcanic activity has occurred during the Holocene
2. A glacier or large ice sheet (>1000 km^2) currently exists

Assuming the current trends of atmospheric warming and glacier retreat continue (Rogelij, 2013), it is reasonable to hypothesise that these highlighted areas may experience a geospheric response to isostatic unloading. While the atmospheric and societal effects of this would in some cases be minimal - increased eruptions in the Antarctic regions, for example, are unlikely to have a significant climatic effect due to their high latitude (Oman et al, 2006), and their remoteness reduces the risk posed to commercial flights - in other areas, such as Canada and Alaska, the impact could be considerably greater, due to the importance of the region for trans-continental and trans-Pacific flights.

6 Conclusions

1. As the subject of rapid climate change becomes ever more pertinent to our society, it is increasingly important to understand how such changes may affect the other aspects that govern the workings of our planet. While the atmosphere, geosphere, cryosphere and other facets of the natural world may be considered separately for the purposes of scientific study, in truth none exist in isolation and each represents only part of a complex, interconnected system. The intricate economical and societal structures we have constructed around the aviation industry alone necessitate a more in-depth knowledge of the interplay between volcanic systems and the climate, highlighting the need for further study.
2. Explosive volcanic eruptions may cause significant climatic cooling effects if sufficient quantities of sulphuric aerosol particles reach the stratosphere. It is thought that some eruptions, such as the 75 kya Toba event, may have caused a series of positive feedback loops, prolonging the initial cooling effect by several centuries and causing migration of the ITCZ with ensuing changes to circulation and precipitation patterns.
3. Though large-scale flood basalt eruptions are frequently linked to long-term climate change and mass extinction events, there is lively debate concerning the cooling influence of SO_2 release versus the greenhouse effect of CO_2. While it has been estimated that 5 x 10^{17} moles of CO_2 may have been emitted during the formation of the Deccan Traps, it has also been argued that this quantity would still have been small in comparison to ambient conditions, and that the effects of the conversion of SO_2 to

sulphuric acid in the stratosphere would have outweighed any warming effects.

4. Isostatic rebound in response to glacial unloading is presented as a viable mechanism for a volcanic response to climate change. Adiabatic melting following deglaciation of Iceland is visible both in historical records and in present-day studies of Vatnajökull. It has been estimated that melt production may have increased between 100-135% since 1890.
5. Studies of tephra and cryptotephra provide invaluable insights into the frequency of volcanic ash cloud occurrences, and may also provide information on the nature of individual eruptions. Current studies of Icelandic ash deposition suggest that eruptions in Iceland which transport significant volumes of ash over continental Europe have a return interval of approximately 56 years, based on depositional records.
6. Numerical models of the 'unloading effect' confirm the hypothesis that crustal uplift in response to deglaciation is very likely to cause increased decompression melting. While increased fracturing and intrusion may provide greater storage capacity for upwelling material in the short-term, most models find that the likelihood of a large volcanic eruption is raised by the retreat of an overlying glacier.

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8 Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

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