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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 explosive and effusive eruptions, such as the 1991 eruption of Mount Pinatubo (Philippines, VEI (Volcanic Explosivity Index) 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 and 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, 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 change in the patterns of volcanic eruption frequency or intensity is relatively unexplored. McGuire (2010) suggests that periods of `exceptional climate change' may be associated with increased levels of hazardous

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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; Óladóttir et al., 2011; Magnusdottir et al., 2013). An increase in volcanic activity as a response to climate change has previously been suggested by multiple studies (Jull and McKenzie, 1996; Pagli and Sigmundsson, 2008; Watson et al., 2016a, 2016b). Such an escalation would have significant consequences, not only for populations in the immediate vicinity of volcanically active regions, but also for the global community as a whole. As of 2014, approximately 100,000 commercial flights occur per day worldwide (ATAG, 2016). Jet aircraft are extremely vulnerable to damage caused by interactions with even low concentrations of airborne ash particles, which may cause electronic failures, or severe abrasion on the turbine fans (Grindle and Burcham, 2003). 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 > 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 2010, which resulted in the closure of a large region of airspace across 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). The presence of volcanic ash also presents a hazard to human health and the health of livestock, particularly with regards to respiratory systems (Horwell and Baxter, 2006), even at relatively small concentrations (Horwell, 2007).

The 2010 eruption of Eyjafjallajökull also precipitated a sudden focus in scientific research into the understanding and mitigation of volcanic ash hazards, particularly with regards to northern Europe and volcanism in Iceland. The unusual geochemical profile of Iceland (a result of its unique geological location above the confluence of a mid-oceanic spreading ridge and a deep-seated mantle plume; Oskarsson et al., 1985) and the relative wealth of data concerning eruptions at the Icelandic sites, in addition to the wide range of locations affected by Icelandic eruptions, make the region ideal for the study of past volcanic activity. Icelandic tephras have been identified in Scotland, England, Ireland, Germany, Sweden, Arctic Norway, Poland, Estonia and the Faroe Islands (Pilcher et al., 2005; Swindles et al., 2011; 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.

This review examines the established links between volcanism and subsequent surface cooling, and assesses the potential for correlation between periods of atmospheric warming and an increase in the frequency of volcanic eruptions, with a focus on Iceland and tephra fallout across northern mainland Europe and the United Kingdom. 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. A wide selection of the existing evidence are considered; however, many of the techniques and hypotheses suggested below are still speculative, and projections of future climate change remain highly contentious at the time of writing (March 2017).

2. Volcano-climate forcing

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. The earliest example of serious 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 following months to the significant negative temperature anomalies which characterised that summer and the following winter. It is now known that the so-called mist 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 and Self, 2003). Once injected into the atmosphere, SO_2 reacts with ambient water vapour to form aerosol mixtures of sulphuric acid (H_2SO_4) and water. This blanketing of the upper atmosphere is believed to have caused significant solar dimming for a period of several months as a result of aerosol particles leading to enhanced scattering of incoming solar radiation (Schmidt, 2013). In the lower atmosphere, sulphur aerosols may also act as cloud condensation nuclei (Jacoby et al., 1999), 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 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 and other climate factors (Self et al., 1981; Robock, 2000). In each case, the eruptions in question were explosive in nature, with a volcanic explosivity index (VEI; a quantitative measurement of the volume of material ejected during an eruption; Newhall and 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 and 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 achieves stratospheric injection (Robock, 2000). These occurrences are often referred to as volcanic aerosol clouds, or `dust veil' events, though in actuality solid particles such as dust and ash make up a relatively small percentage of the active components in volcanically-induced climate change (Lamb, 1970). Such fragments typically have a low residence time (generally on the order of a few months; Robock, 2000) in the atmosphere, and their effects disappear once the particles fall out and settle (Robock, 2000).

The contribution of volcanic gases to atmospheric forcing is much more significant than that of ash particles. The most abundant volcanic gases 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; however, other atmospheric contributors, such as sulphur compounds (e.g. SO_2, H_2S) have a much greater impact. These gases react with ambient OH and H_2O molecules to form aerosols such as H_2SO_4. If carried into the stratosphere by a volcanic column, these particles rapidly achieve global coverage, sometimes circulating the globe in as little as 3 weeks (Robock and Matson, 1983; Bluth et al., 1992). 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). This effect, in addition to aerosol heating by thermal infrared and near-infrared solar radiation, is dominant in the lower stratosphere (Oman et al., 2006). However, the overall net effect of such short-term aerosol releases is always one of mild cooling, typically to $< 1\ ^\circ C$ lower than ambient conditions (Rampino et al., 1988; Santer et al., 2016) (Fig. 1).

The geographic location of the initial eruption also plays a factor in determining an eruption's atmospheric impact (Robock, 2000). Dominant patterns of air circulation enable a more global dispersal of aerosols from tropical eruptions, whereas airborne material from high-