Bulletin of Volcanology (2022) 84:58
https://doi.org/10.1007/s00445-022-01562-8

PERSPECTIVES

Impact of climate change on volcanic processes: current understanding and future challenges

Thomas J. Aubry[1,2] · Jamie I. Farquharson[3] · Colin R. Rowell[4] · Sebastian F. L. Watt[5] · Virginie Pinel[6] · Frances Beckett[7] · John Fasullo[8] · Peter O. Hopcroft[5] · David M. Pyle[9] · Anja Schmidt[1,10,11,12] · John Staunton Sykes[10]

Received: 7 October 2021 / Accepted: 29 March 2022

Abstract
The impacts of volcanic eruptions on climate are increasingly well understood, but the mirror question of how climate changes affect volcanic systems and processes, which we term "climate-volcano impacts", remains understudied. Accelerating research on this topic is critical in view of rapid climate change driven by anthropogenic activities. Over the last two decades, we have improved our understanding of how mass distribution on the Earth's surface, in particular changes in ice and water distribution linked to glacial cycles, affects mantle melting, crustal magmatic processing and eruption rates. New hypotheses on the impacts of climate change on eruption processes have also emerged, including how eruption style and volcanic plume rise are affected by changing surface and atmospheric conditions, and how volcanic sulfate aerosol lifecycle, radiative forcing and climate impacts are modulated by background climate conditions. Future improvements in past climate reconstructions and current climate observations, volcanic eruption records and volcano monitoring, and numerical models all have a role in advancing our understanding of climate-volcano impacts. Important mechanisms remain to be explored, such as how changes in atmospheric circulation and precipitation will affect the volcanic ash life cycle. Fostering a holistic and interdisciplinary approach to climate-volcano impacts is critical to gain a full picture of how ongoing climate changes may affect the environmental and societal impacts of volcanic activity.

Keywords Volcanoes · Climate change · External forcing · Feedbacks

Abstract
Bien que l'impact climatique des éruptions volcaniques soit de mieux en mieux compris, la question de l'impact des changement climatiques sur les processus volcaniques, ou "impacts climat-volcans", reste largement inexplorée. Compte tenu de la

This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

Editorial responsibility: F. Sigmundsson

✉ Thomas J. Aubry
ta460@cam.ac.uk

[1] Department of Geography, University of Cambridge, Cambridge, UK

[2] Sidney Sussex College, Cambridge, UK

[3] Independent, Edinburgh, UK

[4] Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, Canada

[5] School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, UK

[6] IRD, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, Université Gustave Eiffel, ISTerre, Grenoble, France

[7] Met Office, Exeter, UK

[8] National Center for Atmospheric Research, Boulder, CO, USA

[9] Department of Earth Sciences, University of Oxford, Oxford, UK

[10] Department of Chemistry, University of Cambridge, Cambridge, UK

[11] Present Address: German Aerospace Center (DLR), Institute of Atmospheric Physics (IPA), Oberpfaffenhofen, Germany

[12] Present Address: Meteorological Institute, Ludwig-Maximilians University Munich, Munich, Germany

Published online: 18 May 2022

rapidité du changement climatique anthropique, il est critique d'améliorer la compréhension des impacts climat-volcans. Les vingt dernières années de recherche ont permis de mieux charactériser l'impact de la distribution surfacique de masse, par exemple liée aux glaciers et océans, sur les processus tels que la fonte du manteau, la cristallisation magmatiques et les taux éruptifs. De nouveaux mécanismes d'impacts climat-volcans ont aussi été suggérés, y compris l'influence des changements des conditions de surface et atmosphériques sur les styles éruptifs et la dynamique des panaches volcaniques. Le cycle de vie des aérosols volcaniques ainsi que leur forçage radiatif et impacts climatiques sont aussi nuancés par les conditions climatiques dans lesquelles une éruption se produit. Les progrès à venir sur les observations actuelles et reconstructions passées du climat et des éruptions historiques, sur les dispositifs de surveillance des volcans, ainsi que sur les modèles informatiques climatiques et volcaniques vont permettre de mieux comprendre les impacts climat-volcans. Certains mécanismes clés restent mécompris, par exemple l'impact des changements de circulation du vent et de précipitation sur le cycle de vie des cendres volcaniques. Une approche holistique et interdisciplinaire est critique pour établir une vision d'ensemble de l'effet du changement climatique sur les impacts environnementaux et sociaux des éruptions volcaniques.

Introduction

Volcanic eruptions shape Earth's landscapes, have built up Earth's atmosphere and are powerful drivers of environmental and climate change. It has long been known that large volcanic eruptions can affect climate, which we refer to as "volcano-climate impacts", and this constitutes a major research topic (Marshall et al., 2022, this issue). The mirror question, how climate change affects volcanic processes, which we refer to as "climate-volcano impacts", is also not new. It was hypothesised decades ago that volcanic activity could be forced by deglaciation (Hall, 1982; Rampino et al., 1979) or sea-level change (Matthews, 1968; Walcott, 1972). However, the various mechanisms by which climate change may affect volcanic processes remain largely unexplored, despite the topic becoming ever-more relevant in the face of rapid changes in the climate system driven by anthropogenic activities (IPCC, 2021). Improving our understanding of these complex interrelations will in turn improve preparedness for future volcanic crises and enable us to quantify how climate-volcano feedbacks may amplify or dampen anthropogenic climate change (NASEM 2017). This research area is also key to understanding how volcanic processes have been affected by past climate change and, in turn, to improving our understanding of Earth's history.

In this perspective paper, we first highlight progress made over the last two decades in understanding climate-volcano impacts, and then discuss opportunities and challenges for the next decade. The paper is structured around three broad categories of volcanic and magmatic processes:

1) *Pre-eruptive processes* that take place before material is erupted through a vent and are generally associated with spatial scales ranging from the volcanic edifice to regional scale (Fig. 1).
2) *Syn-eruptive processes* that take place after an eruption has started on timescales shorter than or equal to that of the injection of eruptive material into the environment (atmosphere, ocean, or ice), and are generally associated with a spatial scale corresponding to that of the volcanic edifice (Fig. 2).
3) *Post-eruptive processes* that take place after an eruption has started and at timescales longer than that of injection of eruptive material into the environment, and are associated with spatial scales larger than the edifice scale, and up to global scale (Fig. 3).

Owing to the complexities of volcanic systems, some of the processes we discuss are not exclusively associated with a single category proposed above, though an attempt has been made to categorise processes by their dominant association. Last, we assess the level of confidence of each climate-volcano impact mechanism discussed using the following classification:

- *Well understood*: the mechanisms are well defined and supported by robust evidence.
- *Hypothesised*: there is emerging evidence for the mechanism but further research is needed.
- *Uncertain*: we do not know yet how climate change would impact the process, or the impact is highly dependent on the volcanic system considered.

Owing to the emerging nature of the climate-volcano impact field, these qualitative confidence levels are based on our own judgement rather than on quantitative analysis. We report them in square brackets and italics after each mechanism discussed.

Advances made in exploring climate-volcano impacts over the last two decades

Climate-volcano impacts affecting pre-eruptive processes

Figure 1 gives an overview of climate-volcano impacts that affect pre-eruptive processes. Variations in load distribution at

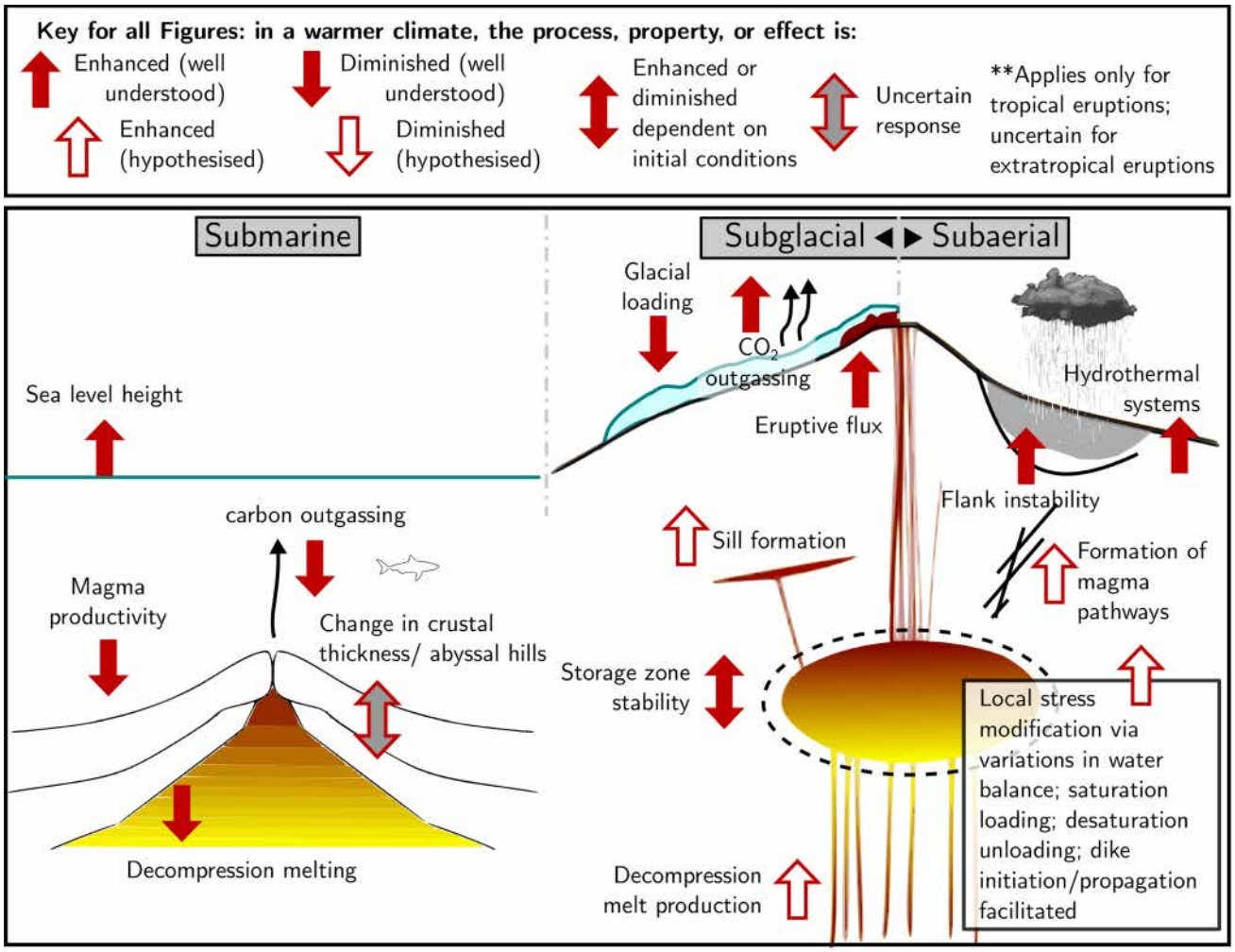

Fig. 1 Schematics illustrating climate-volcano impacts associated with pre-eruptive processes ("Climate-volcano impacts affecting pre-eruptive processes" section) and how they are expected to unfold in the context of a warming climate

the Earth's surface may be brought about due to ice cap melting, sediment deposition and erosion, variations in precipitation intensity, surface water storage and/or sea-level change. Such variations modify the stress state in the underlying crust and potentially into the upper mantle—including pressure, deviatoric stresses and stress orientation—and may thereby influence magma production, transport and eruption (e.g. Mason et al. 2004; Sigmundsson et al., 2013; Watt et al., 2013).

The impacts of ice unloading are controlled by the spatial extent and thickness of ice, the magnitude of ice loss and lithospheric thickness, moderated by the rheology of the crust and mantle (Jull and McKenzie, 1996). In Iceland, volcanic eruption rates following deglaciation are estimated to have increased by as much as 30–50 times relative to the present day (e.g. Maclennan et al., 2002; Sinton et al., 2005; Swindles et al., 2017; but see discussion in Hartley et al., 2016), attributable to temporarily enhanced mantle decompression melting driven by ice unloading. This has been demonstrated by thermo-mechanical modelling (e.g. Jull and McKenzie, 1996; Schmidt et al., 2013; Rees Jones and Rudge, 2020) *[well understood]*, and comparable deglaciation-driven trends following the Last Glacial Maximum have been identified in regional and global eruption records (e.g. Nowell et al., 2006; Huybers and Langmuir, 2009; Lin et al., 2022) *[well understood]*. The predicted decompression rates of glacial isostatic adjustment can be estimated as a function of depth in the melting region, allowing estimation of melt production rates due to deglaciation, which is currently expected to be of the same order of magnitude as tectonic melt production in Iceland (Sigmundsson et al. 2013; Schmidt et al. 2013). This phenomenon may be less pronounced for the thicker lithosphere and flux-melting regimes of arc systems (Watt et al, 2013), but there is evidence that arc volcanoes show temporary post-glacial increases in eruption rate and the eruption of more

evolved magmas (Rawson et al., 2016). This may be driven by crustal stress regimes that promote magma storage during glaciation and subsequently enhanced ascent following ice retreat (Watt et al., 2013; cf. Jellinek et al., 2004). This is supported by mechanical models characterizing the effect of ice-related stress variations on magma transport towards the surface (Michaut and Pinel, 2018) *[well understood]*, and the stability of crustal magma storage zones (Sigmundsson et al., 2010, 2013) *[well understood]*. As a counterpart to ice retreat, sea-level rise (Fasullo and Nerem, 2018) may also decrease mantle melting rates and carbon outgassing at mid-ocean ridges on glacial timescales (Crowley et al., 2015; Tolstoy, 2015; Boulahanis et al., 2020) *[hypothesised]*. More generally, eruptive records show periodicities consistent with orbital scale climatic cycles (Schindlbeck et al., 2018), supporting relationships between hydrospheric mass distribution and magmatism. On the scale of individual edifices, ice retreat and sea-level change may influence flank stability (Quidelleur et al., 2008; Coussens et al., 2016) *[hypothesised]*, magma migration (Hooper et al, 2011; Michaut et al. 2020) *[hypothesised]* and the eruptibility of magma (Satow et al., 2021) by changing ocean bottom pressure and crustal stress conditions *[hypothesised]*. More generally, surface load distributions influence the balance between crustal magma storage and ascent, but the direction of these changes is highly dependent on the storage zone size, depth and shape as well as on the magma compressibility and lithospheric rheology (Albino et al, 2010; Sigmundsson et al, 2013) *[uncertain]*.

Continued global warming is also projected to cause regional and global increases in extreme rainfall over the next century (Fischer et al. 2014; Pfahl et al. 2017). Extreme rainfall has been linked to induced volcanic activity in multiple case studies (e.g. McKee et al., 1981; Barclay et al., 2006; Matthews et al., 2002, 2009). Theorised mechanisms operate from minutes to millennia, including shallow-seated processes (e.g. fuel–coolant interactions: Elsworth et al., 2004; Simmons et al., 2004; Taron et al., 2007) [*well understood*] associated with volumetric expansion of volatiles and steam-driven explosions, with pressurisation and weakening facilitated by thermal contraction (Mastin, 1994; Elsworth et al. 2004; Yamasato et al., 1998) [*well understood*]. Flank collapse can be promoted by precipitation-induced erosion, failure plane weakening and hydrothermal alteration (e.g. Kerle et al. 2003; Capra, 2006; Tost and Cronin, 2016; Romero et al., 2021) [*well understood*]. We note that flank instability can be viewed as a pre-, syn- or post-eruptive process (Fig. 2). Subsurface infiltration of meteoric water may foster deep-seated primary volcanic activity via variations in overburden stress, mechanical failure of the magma chamber wall and pore pressure–driven generation of magma pathways throughout the edifice (e.g. Violette et al. 2001; Albino et al., 2018; Farquharson and Amelung, 2020; Heap et al., 2021) [*hypothesised*].

Climate-volcano impacts affecting syn-eruptive processes

Figure 2 gives an overview of climate-volcano impacts that affect syn-eruptive processes. The height at which volcanic columns inject ash and gas into the atmosphere governs ash-related hazard (Harvey et al., 2018) and sulfate aerosol climate impacts (Marshall et al., 2019). For tropical eruptions, the projected increase in tropospheric stratification and tropopause height may reduce the height of tropospheric volcanic plumes and volcanic stratospheric injections, but decreasing stratospheric stratification may increase the height of stratospheric volcanic plumes (Aubry et al., 2016; 2019) *[hypothesised]*. Changes in wind speed will exert a greater influence on extratropical volcanic plumes relative to tropical ones (Aubry et al., 2016) *[hypothesised]*.

Changes in the surface distribution of water and ice may also alter syn-eruptive processes and the SO_2 life cycle in the volcanic column and cloud via direct magma-water interaction (i.e. hydrovolcanism) *[hypothesised]*. Hydrostatic pressure from overlying water and ice can suppress explosive behaviour and drive transitions towards effusive eruptions (Cas and Simmons, 2018) *[well understood]*. Incorporation of water into eruption columns alters plume heights, induces column collapse and increases the amount of fine ash and water injected into the atmosphere along with SO_2 (Koyaguchi and Woods, 1996; Mastin 2007; Van Eaton et al., 2012; Rowell et al., in press). Increasing fine ash and water content, in turn, promotes conditions for scrubbing of SO_2 by ash (Ayris et al., 2013; Schmauss and Keppler, 2014), modifies the life cycle of sulfate aerosols (LeGrande et al., 2016; Zhu et al., 2020) and directly impacts climate by stratospheric loading of water vapour (Forster and Shine, 2002; Joshi and Jones, 2009). Despite observations in unprecedented detail of hydrovolcanic processes from recent eruptions (e.g. Magnusson et al., 2012; Prata et al., 2017; Gouhier and Paris, 2019; Lopez et al., 2020), a comprehensive assessment of links between observed hydrovolcanic events and the fate of volcanic SO_2 remains to be completed. The Hunga Tonga-Hunga Ha'apai 2022 eruption may help achieve significant progress on this question.

Climate-volcano impacts affecting post-eruptive processes

Climate-volcano impacts affecting post-eruptive processes are summarised in Fig. 3. Existing studies have focused on the life cycle and climatic impacts of volcanic sulfate aerosols. Due to the current abundance of anthropogenic

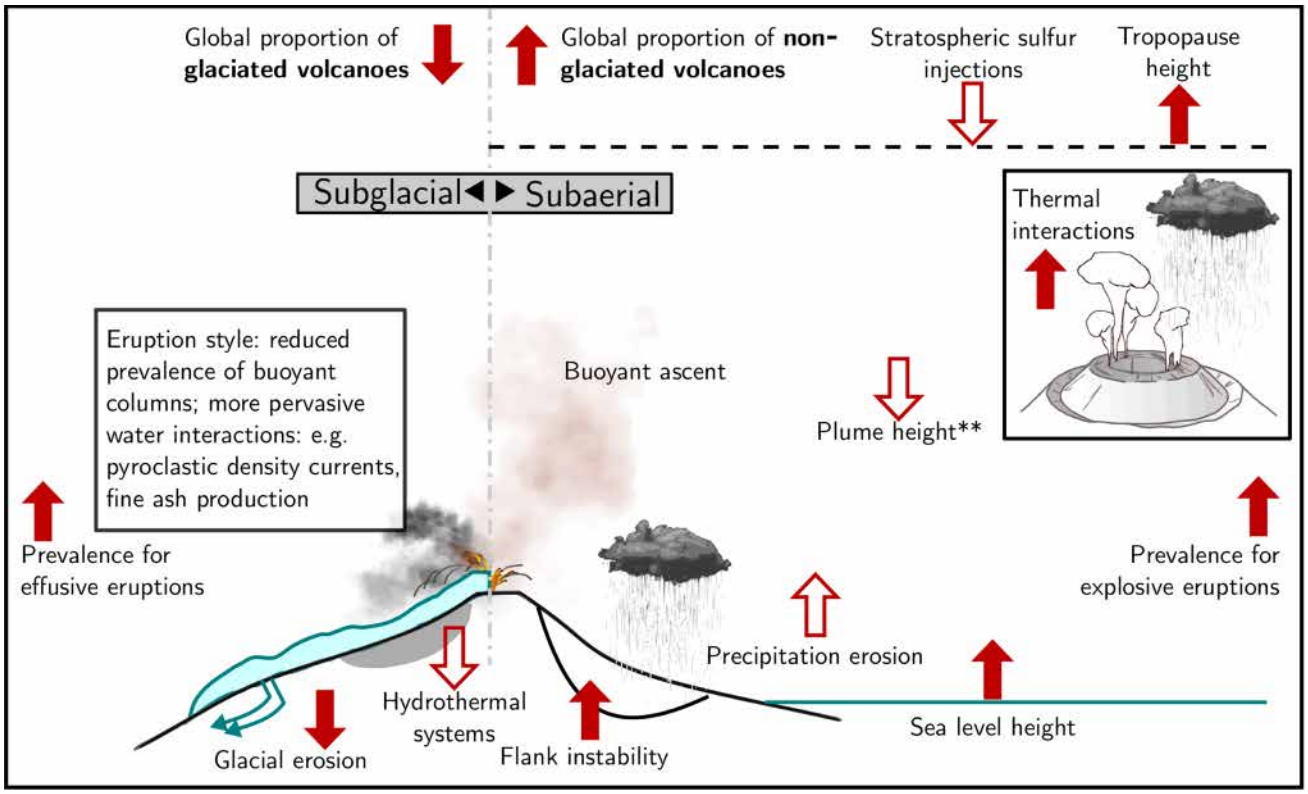

Fig. 2 Schematics illustrating climate-volcano impacts associated with pre-eruptive processes ("Climate-volcano impacts affecting pre-eruptive processes" section) and how they are expected to unfold in the context of a warming climate. The same as Fig. 1 but for climate-volcano impacts affecting syn-eruptive processes

tropospheric aerosol, the impact of tropospheric volcanic aerosol on radiative forcing is halved compared to pre-industrial climates (Schmidt et al., 2012) *[well understood]*. This highlights a mechanism through which atmospheric aerosol pollution, not climate change, modulates a volcanic process. Aubry et al. (2021a) showed that ongoing climate change could lead to an amplification of the radiative forcing of stratospheric sulfate aerosols from large-magnitude tropical eruptions *[hypothesised]*. This is a consequence of plume height increase (see section on syn-eruptive processes) and the acceleration of the Brewer-Dobson circulation which decreases the residence time of aerosol in the tropical reservoir leading to less coagulation and smaller aerosol particles which backscatter sunlight more efficiently. Fasullo et al. (2017) also showed that the surface cooling response to tropical eruptions is enhanced in a warmer climate because of the stronger ocean stratification and reduced penetration of volcanic cooling in the ocean, which in turn enhances the cooling of the atmosphere at the surface *[hypothesised]*. Hopcroft et al. (2018) showed that increased anthropogenic pollution resulted in an increase in tropospheric albedo and a decrease of the effective radiative forcing from stratospheric volcanic sulfate aerosols *[hypothesised]*. Last, solar radiation management via stratospheric aerosol injection—one of the most discussed geo-engineering strategies (Kravitz et al., 2015)—could cause volcanic aerosols to directly condense onto pre-existing geo-engineered particles, resulting in larger aerosol particles and in turn a decreased and faster-decaying radiative forcing (Laakso et al., 2016) *[well understood]*.

Progress and challenges for the coming decade

Over the next decade, continuous improvement in both climate and volcanological observations and past records will advance our understanding of processes through which climate affects volcanic systems, as well as how climate-volcano impacts unfolded in the past. Better spatio-temporal coverage and resolution of spaceborne observations of precipitation and ice mass (e.g. Dussaillant et al., 2019; Velicogna et al., 2020; Kidd et al., 2021) will allow a shift towards holistic data-rich studies that examine the influence of rainfall patterns, glacial wastage and ice cap melt, and sea-level change on volcanic systems, from local to global scales. This information will potentially lead to an

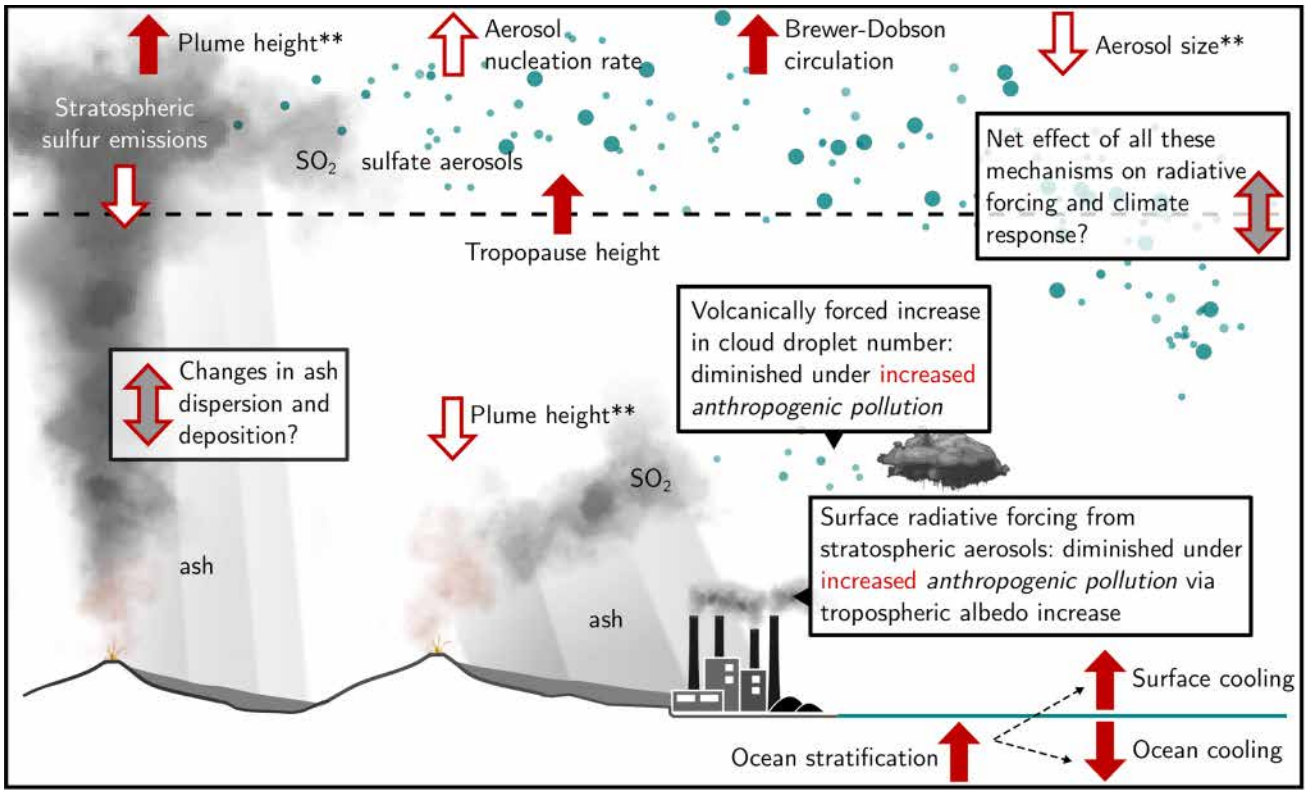

Fig. 3 Schematics illustrating climate-volcano impacts associated with pre-eruptive processes ("Climate-volcano impacts affecting pre-eruptive processes" section) and how they are expected to unfold in the context of a warming climate. The same as Fig. 1 but for climate-volcano impacts affecting post-eruptive processes

update of glacial isostatic adjustment and melt productivity models in volcanic areas (Schmidt et al., 2013). The advancement of spaceborne and in-situ volcanic gas and aerosol measurements (e.g. Carn et al. 2018; Theys et al. 2019; Liu et al. 2020) will also help to rigorously quantify SO_2 budgets during eruptions to assess the efficiency with which SO_2, water and ash are dispersed to the atmosphere under different environmental conditions (e.g. Sigmarsson et al., 2013; Legrande et al., 2016; Lopez et al., 2020). Experimental studies should further explore how SO_2 interacts with ash and hydrometeors across a parameter space of temperature, pressure and humidity. Databases gathering both volcanological and climate information are also being developed (e.g. the IVESPA database, Aubry et al. 2021b) and will advance our understanding of, for example, how meteorological conditions affect plume rise. Beyond direct observations, volcanic records and climate proxy records are also improving (e.g. Baldini et al. 2015; Lin et al. 2022; Sigl et al. 2021; Büntgen et al. 2021). A better time resolution of these records may for example help clarify the mechanisms and time lags associated with the impacts of changes in ice load or sea-level on magmatic processes. This would in turn promote an understanding of the mechanisms' responses to climate change and the timescales on which those responses would act.

Improvements in numerical models will also be required to better understand climate-volcano impacts. Thermo-mechanical models studying the effect of climate change on magma plumbing systems should integrate the complex rheology associated with the new vision of trans-crustal magmatic systems (Cashman et al, 2017). We also need 3D simulations of eruption columns in future climates that incorporate physical transport, chemistry and microphysics, assessing outcomes for vertical mass distribution and chemical fate of SO_2, ash and water. An increasing number of aerosol-chemistry-climate models can interactively simulate the volcanic sulfate aerosol lifecycle (Timmreck, 2012) and its interaction with volcanic water (LeGrande et al., 2016) and ash (Zhu et al., 2020). Beyond models themselves, the continuous improvement of high-performance computing facilities and data storage and analysis will facilitate the investigation of climate-volcano impacts at centennial-millennial timescales and with multimodel ensembles. For example, multi-model approaches are required to assess whether currently hypothesised impacts

of climate change on volcanic aerosol forcing (Aubry et al., 2021a) and climatic impacts (Fasullo et al. 2017; Hopcroft et al. 2018) are robust. The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP, Zanchettin et al., 2016) has already begun to examine this but does not yet account for interactions related to plume dynamics and aerosol microphysics and chemistry.

Regardless of improvements in observations and models, some climate-induced changes in volcanic processes may be subtle compared to observational uncertainties and variability in eruption style and conditions. The low recurrence rate of large explosive eruptions (e.g. 50–100 years for Volcanic Explosivity Index 6, Newhall et al., 2018) also means that only a handful of large-magnitude eruptions have occurred during the observational period, making it even more challenging to support model-derived hypotheses on climate-volcano impacts with observational evidence. Methodologies employed for extreme event attribution in climate science (Otto, 2017) could be explored to test whether there is a detectable influence of climate change on future eruptions.

Lastly, a number of potential yet critical climate-volcano impacts remain unexplored, such as the impact of climate change on processes related to lava flows, non-sulfur gases (e.g. halogens) or ash. The ash question is particularly motivated by implications for hazard management and by the fact that current atmospheric circulation patterns cannot account for the spatial distribution of tephra deposits during the Pliocene and Pleistocene glacial periods (Sigurdsson et al., 1990; Lacasse, 2001; Lacasse and van den Bogaard, 2002). The dominant transport patterns of volcanic ash clouds and their residence time in the atmosphere may be altered by future changes in atmospheric circulation and precipitation. Aforementioned (see section on syn-eruptive processes) climate-induced changes in plume height (Aubry et al., 2016) and grain-size distribution (Osman et al., 2020) would also affect dispersion patterns. Lahars and airborne remobilisation of volcanic deposits are also dependent on extreme and seasonal rainfall (e.g. Kataoka et al., 2018; Paguican et al., 2009; Jarvis et al., 2020) and could be affected by climate change.

Concluding remarks

The recently released Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that depending on the amount of greenhouse gas emissions, the global surface temperature is very likely to be higher by 1.0 °C to 5.7 °C by 2100 compared to 1850–1900 (IPCC, 2021), and the committed warming may even be as high as 2.0 °C (Zhou et al. 2021). The IPCC report also highlights that with every increment of global warming, changes in climatic factors that directly impact volcanic processes get larger. This includes ice sheet melting, sea level rise, the acceleration of the Brewer-Dobson circulation, or more frequent and intense extreme precipitation events. Such projections highlight the urgency to accelerate research on climate-volcano impacts, which remain a relatively niche topic to date. Of critical importance is to quantify the extent to which magmatic and volcanic processes will be affected by climate change, and the spatial and temporal scale of these effects. This will in turn enable better preparedness for the potential consequences of climate-volcano impacts, including exacerbated volcanic hazards, societal impacts and economic repercussions, as well as climate-volcano feedback loops that could amplify or dampen climate change driven by anthropogenic activities.

Acknowledgements We sincerely thank Alan Robock and Michelle Parks for their feedback that helped to improve our manuscript, and Claire Witham and Lauren Marshall for their insightful comments on an early version of this paper.

Author contribution Conceptualization: T. J. A. with inputs from all authors.
Figures: J. I. F. with inputs from all authors.
Writing: All authors.

Funding T. J. A. acknowledges support from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 835939, and from the Sidney Sussex college through a Junior Research Fellowship. C. R. R. was funded through an Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery grant to A. M. Jellinek. P. O. H. is supported by a Birmingham Fellowship. D. M. P. is supported by the UK Natural Environment Research Council (NERC) Centre for the Observation and Modelling of Earthquakes, Volcanoes, and Tectonics (COMET). A. S. was funded by NERC grants NE/S000887/1 (VOLCLIM) and NE/S00436X/1 (V-PLUS). The efforts of J. Fasullo were supported by NASA Award 80NSSC17K0565, by NSF Award #AGS-1419571, and by the Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modeling Program of the US Department of Energy's Office of Biological & Environmental Research (BER) via National Science Foundation IA 1947282.

Data Availability Not applicable.

Code availability Not applicable.

Declarations

Additional declarations for articles in life science journals that report the results of studies involving humans and/or animals Not applicable.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Albino F, Amelung F, Gregg P (2018) The role of pore fluid pressure on the failure of magma reservoirs: insights from Indonesian and Aleutian arc volcanoes. J Geophys Res Solid Earth 123:1328–1349. https://doi.org/10.1002/2017JB014523

Albino F, Pinel V, Sigmundsson F (2010) Influence of surface load variations on eruption likelihood: application to two Icelandic subglacial volcanoes, Grímsvötn and Katla. Geophys J Int 181:1510–1524. https://doi.org/10.1111/j.1365-246X.2010.04603.x

Aubry TJ, Jellinek AM, Degruyter W, et al (2016) Impact of global warming on the rise of volcanic plumes and implications for future volcanic aerosol forcing. J Geophys Res Atmos 121:13,326–13,351. https://doi.org/10.1002/2016JD025405

Aubry TJ, Cerminara M, Jellinek AM (2019) Impacts of climate change on volcanic stratospheric injections: comparison of 1-D and 3-D plume model projections. Geophys Res Lett 46:10609–10618. https://doi.org/10.1029/2019GL083975

Aubry TJ, Staunton-Sykes J, Marshall LR et al (2021a) Climate change modulates the stratospheric volcanic sulfate aerosol lifecycle and radiative forcing from tropical eruptions. Nat Commun 12:4708. https://doi.org/10.1038/s41467-021-24943-7

Aubry TJ, Engwell S, Bonadonna C, et al (2021b) The Independent Volcanic Eruption Source Parameter Archive (IVESPA, version 1.0): a new observational database to support explosive eruptive column model validation and development. J Volcanol Geothermal Res 417:107295. https://doi.org/10.1016/j.jvolgeores.2021b.107295

Ayris PM, Lee AF, Wilson K et al (2013) SO2 sequestration in large volcanic eruptions: High-temperature scavenging by tephra. Geochim Cosmochim Acta 110:58–69. https://doi.org/10.1016/j.gca.2013.02.018

Baldini LM, McDermott F, Baldini JUL et al (2015) Regional temperature, atmospheric circulation, and sea-ice variability within the Younger Dryas Event constrained using a speleothem from northern Iberia. Earth Planet Sci Lett 419:101–110. https://doi.org/10.1016/j.epsl.2015.03.015

Barclay J, Johnstone JE, Matthews AJ (2006) Meteorological monitoring of an active volcano: Implications for eruption prediction. J Volcanol Geoth Res 150:339–358. https://doi.org/10.1016/j.jvolgeores.2005.07.020

Boulahanis B, Carbotte SM, Huybers PJ et al (2020) Do sea level variations influence mid-ocean ridge magma supply? A test using crustal thickness and bathymetry data from the East Pacific Rise. Earth Planet Sci Lett 535:116121. https://doi.org/10.1016/j.epsl.2020.116121

Büntgen U, Allen K, Anchukaitis KJ et al (2021) The influence of decision-making in tree ring-based climate reconstructions. Nat Commun 12:3411. https://doi.org/10.1038/s41467-021-23627-6

Capra L (2006) Abrupt climate changes as triggering mechanisms of massive volcanic collapses. J Volcanol Geoth Res 155:329–333. https://doi.org/10.1016/j.jvolgeores.2006.04.009

Carn SA, Krotkov NA, Fisher BL, et al (2018) First observations of volcanic eruption clouds from the L1 Earth-Sun Lagrange Point by DSCOVR/EPIC. Geophys Res Lett 45:11,456–11,464. https://doi.org/10.1029/2018GL079808

Cas RAF, Simmons JM (2018) Why deep-water eruptions are so different from subaerial eruptions. Front Earth Sci 6:198. https://doi.org/10.3389/feart.2018.00198

Cashman KV, Sparks RSJ, Blundy JD (2017) Vertically extensive and unstable magmatic systems: a unified view of igneous processes. Science 355:eaag3055. https://doi.org/10.1126/science.aag3055

Coussens M, Wall-Palmer D, PeterJ T et al (2016) The relationship between eruptive activity, flank collapse, and sea level at volcanic islands: a long-term (>1 Ma) record offshore Montserrat, Lesser Antilles. Geochem Geophys Geosyst 17:2591–2611. https://doi.org/10.1002/2015GC006053

Crowley JW, Katz RF, Huybers P et al (2015) Glacial cycles drive variations in the production of oceanic crust. Science 347:1237–1240. https://doi.org/10.1126/science.1261508

Dussaillant I, Berthier E, Brun F et al (2019) Two decades of glacier mass loss along the Andes. Nat Geosci 12:802–808. https://doi.org/10.1038/s41561-019-0432-5

Elsworth D, Voight B, Thompson G, Young SR (2004) Thermal-hydrologic mechanism for rainfall-triggered collapse of lava domes. Geology 32:969–972. https://doi.org/10.1130/G20730.1

Farquharson JI, Amelung F (2020) Extreme rainfall triggered the 2018 rift eruption at Kīlauea Volcano. Nature 580:491–495. https://doi.org/10.1038/s41586-020-2172-5

Fasullo JT, Nerem RS (2018) Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. PNAS 115:12944–12949. https://doi.org/10.1073/pnas.1813233115

Fasullo JT, Tomas R, Stevenson S et al (2017) The amplifying influence of increased ocean stratification on a future year without a summer. Nat Commun 8:1236. https://doi.org/10.1038/s41467-017-01302-z

Fischer EM, Sedláček J, Hawkins E, Knutti R (2014) Models agree on forced response pattern of precipitation and temperature extremes. Geophys Res Lett 41:8554–8562. https://doi.org/10.1002/2014GL062018

Forster, P.M. de F., Shine, K.P., (2002) Assessing the climate impact of trends in stratospheric water vapor. Geophys Res Lett 29, 10–1–10–4. https://doi.org/10.1029/2001GL013909

Gouhier M, Paris R (2019) SO2 and tephra emissions during the December 22, 2018 Anak Krakatau eruption. Volcanica 2:91–103. https://doi.org/10.30909/vol.02.02.91103

Hall K (1982) Rapid deglaciation as an initiator of volcanic activity: an hypothesis. Earth Surf Proc Land 7:45–51. https://doi.org/10.1002/esp.3290070106

Hartley ME, Thordarson T, de Joux A (2016) Postglacial eruptive history of the Askja region. North Iceland Bull Volcanol 78:28. https://doi.org/10.1007/s00445-016-1022-7

Harvey NJ, Huntley N, Dacre HF et al (2018) Multi-level emulation of a volcanic ash transport and dispersion model to quantify sensitivity to uncertain parameters. Nat Hazard 18:41–63. https://doi.org/10.5194/nhess-18-41-2018

Heap MJ, Baumann T, Gilg HA et al (2021) Hydrothermal alteration can result in pore pressurization and volcano instability. Geology. https://doi.org/10.1130/G49063.1

Hooper A, Ófeigsson B, Sigmundsson F et al (2011) Increased capture of magma in the crust promoted by ice-cap retreat in Iceland. Nature Geosci 4:783–786. https://doi.org/10.1038/ngeo1269

Hopcroft PO, Kandlbauer J, Valdes PJ, Sparks RSJ (2018) Reduced cooling following future volcanic eruptions. Clim Dyn 51:1449–1463. https://doi.org/10.1007/s00382-017-3964-7

Huybers P, Langmuir C (2009) Feedback between deglaciation, volcanism, and atmospheric CO2. Earth Planet Sci Lett 286:479–491. https://doi.org/10.1016/j.epsl.2009.07.014

PA Jarvis C Bonadonna L Dominguez P Forte C Frischknecht D Bran R Aguilar F Beckett M Elissondo J Gillies U Kueppers J Merrison N Varley KL Wallace 2020 Aeolian remobilisation of volcanic ash: outcomes of a workshop in the Argentinian Patagonia Front Earth Sci 8 https://doi.org/10.3389/feart.2020.575184

Jellinek AM, Manga M, Saar MO (2004) Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. J Geophys Res Solid Earth 109:B09206. https://doi.org/10.1029/2004JB002978

Joshi MM, Jones GS (2009) The climatic effects of the direct injection of water vapour into the stratosphere by large volcanic eruptions. Atmos Chem Phys 9:6109–6118. https://doi.org/10.5194/acp-9-6109-2009

Jull M, McKenzie D (1996) The effect of deglaciation on mantle melting beneath Iceland. J Geophys Res Solid Earth 101:21815–21828. https://doi.org/10.1029/96JB01308

Kataoka KS, Matsumoto T, Saito T et al (2018) Lahar characteristics as a function of triggering mechanism at a seasonally snow-clad volcano: contrasting lahars following the 2014 phreatic eruption of Ontake Volcano. Japan Earth Planets Space 70:113. https://doi.org/10.1186/s40623-018-0873-x

N Kerle van Wyk de Vries, B. and Oppenheimer, C. 2003 New insight into the factors leading to the 1998 flank collapse and lahar disaster at Casita volcano Nicaragua Bull Volcanol 65 5 331 345 https://doi.org/10.1007/s00445-002-0263-9

Kidd C, Huffman G, Maggioni V, Chambon P, Oki R (2021) The Global Satellite Precipitation Constellation: current status and future requirements. Bull Am Meteor Soc 102(10):E1844–E1861. https://doi.org/10.1175/BAMS-D-20-0299.1

Koyaguchi T, Woods AW (1996) On the formation of eruption columns following explosive mixing of magma and surface-water. J Geophys Res Solid Earth 101:5561–5574. https://doi.org/10.1029/95JB01687

Kravitz B, Robock A, Tilmes S et al (2015) The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): simulation design and preliminary results. Geosci Model Develop 8:3379–3392. https://doi.org/10.5194/gmd-8-3379-2015

Laakso A, Kokkola H, Partanen A-I et al (2016) Radiative and climate impacts of a large volcanic eruption during stratospheric sulfur geoengineering. Atmos Chem Phys 16:305–323. https://doi.org/10.5194/acp-16-305-2016

Lacasse C (2001) Influence of climate variability on the atmospheric transport of Icelandic tephra in the subpolar North Atlantic. Global Planet Change 29:31–55. https://doi.org/10.1016/S0921-8181(01)00099-6

Lacasse C, van den Bogaard P (2002) Enhanced airborne dispersal of silicic tephras during the onset of Northern Hemisphere glaciations, from 6 to 0 Ma records of explosive volcanism and climate change in the subpolar North Atlantic. Geology 30:623–626. https://doi.org/10.1130/0091-7613(2002)030%3c0623:EADOST%3e2.0.CO;2

LeGrande AN, Tsigaridis K, Bauer SE (2016) Role of atmospheric chemistry in the climate impacts of stratospheric volcanic injections. Nature Geosci 9:652–655. https://doi.org/10.1038/ngeo2771

Lin J, Svensson A, Hvidberg CS, Lohmann J, Kristiansen S, Dahl-Jensen D, Steffensen JP, Rasmussen SO, Cook E, Kjær HA, Vinther BM, Fischer H, Stocker T, Sigl M, Bigler M, Severi M, Traversi R, Mulvaney R (2022) Magnitude, frequency and climate forcing of global volcanism during the last glacial period as seen in Greenland and Antarctic ice cores (60–9 ka). Clim past 18:485–506. https://doi.org/10.5194/cp-18-485-2022

EJ Liu A Aiuppa A Alan et al 2020 Aerial strategies advance volcanic gas measurements at inaccessible, strongly degassing volcanoes SciAdv 6 https://doi.org/10.1126/sciadv.abb9103

Lopez T, Clarisse L, Schwaiger H et al (2020) Constraints on eruption processes and event masses for the 2016–2017 eruption of Bogoslof volcano, Alaska, through evaluation of IASI satellite SO2 masses and complementary datasets. Bull Volcanol 82:17. https://doi.org/10.1007/s00445-019-1348-z

Maclennan J, Jull M, McKenzie D et al (2002) The link between volcanism and deglaciation in Iceland. Geochem Geophys Geosyst 3:1–25. https://doi.org/10.1029/2001GC000282

E Magnússon MT Gudmundsson MJ Roberts et al 2012 Ice-volcano interactions during the 2010 Eyjafjallajökull eruption, as revealed by airborne imaging radar J Geophys Res Solid Earth 117 https://doi.org/10.1029/2012JB009250

Marshall L, Johnson JS, Mann GW et al (2019) Exploring how eruption source parameters affect volcanic radiative forcing using statistical emulation. J Geophys Res Atmos 124:964–985. https://doi.org/10.1029/2018JD028675

Marshall LR, Maters E, Schmidt A, Timmreck C, Robock A, Toohey M (2022) Volcanic effects on climate: looking backward and forward, under review for Bulletin of Volcanology (this issue)

BG Mason DM Pyle WB Dade T Jupp 2004 Seasonality of volcanic eruptions J Geophys Res Solid Earth 109 https://doi.org/10.1029/2002JB002293

Mastin LG (1994) Explosive tephra emissions at Mount St. Helens, 1989–1991: The violent escape of magmatic gas following storms? GSA Bull 106:175–185. https://doi.org/10.1130/0016-7606(1994)106%3c0175:ETEAMS%3e2.3.CO;2

LG Mastin 2007 A user-friendly one-dimensional model for wet volcanic plumes Geochem Geophys Geosyst 8 https://doi.org/10.1029/2006GC001455

Matthews AJ, Barclay J, Carn S, et al (2002) Rainfall-induced volcanic activity on Montserrat. Geophys Res Lett 29:22–1–22–4. https://doi.org/10.1029/2002GL014863

Matthews AJ, Barclay J, Johnstone JE (2009) The fast response of volcano-seismic activity to intense precipitation: triggering of primary volcanic activity by rainfall at Soufrière Hills Volcano, Montserrat. J Volcanol Geoth Res 184:405–415. https://doi.org/10.1016/j.jvolgeores.2009.05.010

Matthews RK (1968) Tectonic implications of glacio-eustatic sea level fluctuations. Earth Planet Sci Lett 5:459–462. https://doi.org/10.1016/S0012-821X(68)80079-2

McKee CO, Wallace DA, Almond RA, Talai B (1981) Fatal hydro-eruption of Karkar volcano in 1979: development of a maar-like crater. Cooke-Ravian Vol Volcanol Papers Geol Survey Papua New Guinea 10:63–84

Michaut C, Pinel V (2018) Magma ascent and eruption triggered by cratering on the moon. Geophys Res Lett 45:6408–6416. https://doi.org/10.1029/2018GL078150

Michaut C, Pinel V, Maccaferri F (2020) Magma ascent at floor-fractured craters diagnoses the lithospheric stress state on the Moon. Earth Planet Sci Lett 530:115889. https://doi.org/10.1016/j.epsl.2019.115889

National Academies of Sciences, Engineering, and Medicine (2017) Volcanic eruptions and their repose, unrest, precursors, and timing. National Academies Press

Newhall C, Self S, Robock A (2018) Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts. Geosphere 14:572–603. https://doi.org/10.1130/GES01513.1

Nowell DAG, Jones MC, Pyle DM (2006) Episodic Quaternary volcanism in France and Germany. J Quat Sci 21:645–675. https://doi.org/10.1002/jqs.1005

Osman S, Beckett F, Rust A, Snee E (2020) Sensitivity of volcanic ash dispersion modelling to input grain size distribution based on hydromagmatic and magmatic deposits. Atmosphere 11:567. https://doi.org/10.3390/atmos11060567

Otto FEL (2017) Attribution of weather and climate events. Ann Rev Environ Resour 42:627–646. https://doi.org/10.1146/annurev-environ-102016-060847

Paguican EMR, Lagmay AMF, Rodolfo KS et al (2009) Extreme rainfall-induced lahars and dike breaching, 30 November 2006, Mayon Volcano, Philippines. Bull Volcanol 71:845–857. https://doi.org/10.1007/s00445-009-0268-8

Pfahl S, O'Gorman PA, Fischer EM (2017) Understanding the regional pattern of projected future changes in extreme precipitation. Nat Clim Chang 7:423–427. https://doi.org/10.1038/nclimate3287

Prata F, Woodhouse M, Huppert HE et al (2017) Atmospheric processes affecting the separation of volcanic ash and SO_2 in volcanic eruptions: inferences from the May 2011 Grímsvötn eruption. Atmos Chem Phys 17:10709–10732. https://doi.org/10.5194/acp-17-10709-2017

X QuidelleurA Hildenbrand A Samper 2008 Causal link between Quaternary paleoclimate changes and volcanic islands evolution Geophys Res Lett 35 https://doi.org/10.1029/2007GL031849

Rampino MR, Self S, Fairbridge RW (1979) Can rapid climate change cause volcanic eruptions? Science 206:826–829. https://doi.org/10.1126/science.206.4420.826

Rawson H, Pyle DM, Mather TA et al (2016) The magmatic and eruptive response of arc volcanoes to deglaciation: Insights from southern Chile. Geology 44:251–254. https://doi.org/10.1130/G37504.1

Rees Jones DW, Rudge JF (2020) Fast magma ascent, revised estimates from the deglaciation of Iceland. Earth Planet Sci Lett 542:116342

Romero JE, Polacci M, Watt S et al (2021) Volcanic lateral collapse processes in mafic arc edifices: a review of their driving processes, types and consequences. Front Earth Sci 9:639825. https://doi.org/10.3389/feart.2021.639825

Rowell C, Jellinek AM, Hajimirza S, and Aubry TJ, External surface water influence on explosive eruption dynamics, with implications for stratospheric sulfur delivery and volcano-climate feedback, in press for Frontiers Earth Sci https://doi.org/10.13140/RG.2.2.33030.09288

Satow C, Gudmundsson A, Gertisser R et al (2021) Eruptive activity of the Santorini Volcano controlled by sea-level rise and fall. Nat Geosci 14:586–592. https://doi.org/10.1038/s41561-021-00783-4

Schindlbeck JC, Kutterolf S, Freundt A et al (2018) Miocene to Holocene marine tephrostratigraphy offshore northern central America and Southern Mexico: pulsed activity of known volcanic complexes. Geochem Geophys Geosyst 19:4143–4173. https://doi.org/10.1029/2018GC007832

Schmauss D, Keppler H (2014) Adsorption of sulfur dioxide on volcanic ashes. Am Miner 99:1085–1094. https://doi.org/10.2138/am.2014.4656

Schmidt A, Carslaw KS, Mann GW et al (2012) Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate. Atmos Chem Phys 12:7321–7339. https://doi.org/10.5194/acp-12-7321-2012

Schmidt P, Lund B, Hieronymus C, Maclennan J, Árnadóttir T, Pagli C (2013) Effects of present-daydeglaciation in Iceland on mantle melt production rates. J Geophys Res Solid Earth 118:3366–3379. https://doi.org/10.1002/jgrb.50273

M Sigl M Toohey J McConnell R; Cole-Dai, Jihong; Severi, Mirko, 2021 HolVol: Reconstructed volcanic stratospheric sulfur injections and aerosol optical depth for the Holocene (9500 BCE to 1900 CE) PANGAEA 10.1594/PANGAEA.928646

Sigmarsson O, Haddadi B, Carn S et al (2013) The sulfur budget of the 2011 Grímsvötn eruption, Iceland. Geophys Res Lett 40:6095–6100. https://doi.org/10.1002/2013GL057760

Sigmundsson F, Albino F, Schmidt P, et al (2013) Multiple effects of ice load changes and associated stress change on magmatic systems. In: Clim Forc Geol Hazards. John Wiley & Sons, Ltd, pp 108–123

Sigmundsson F, Pinel V, Lund B et al (2010) Climate effects on volcanism: influence on magmatic systems of loading and unloading from ice mass variations, with examples from Iceland. Philos Trans Royal Soc Math Phys Eng Sci 368:2519–2534. https://doi.org/10.1098/rsta.2010.0042

Sigurdsson H (1990) Evidence of volcanic loading of the atmosphere and climate response. Global Planet Change 3:277–289. https://doi.org/10.1016/0921-8181(90)90024-7

Simmons J, Elsworth D, Voight B (2004) Instability of exogenous lava lobes during intense rainfall. Bull Volcanol 66:725–734. https://doi.org/10.1007/s00445-004-0353-y

J Sinton K Grönvold K Sæmundsson 2005 Postglacial eruptive history of the Western Volcanic Zone, Iceland GeochemGeophys Geosyst 6 https://doi.org/10.1029/2005GC001021

Swindles GT, Watson EJ, Savov IP, Lawson IT, Schmidt A, Hooper A, Cooper CL, Connor CB, Gloor M, Jonathan L (2017) Carrivick; Climatic control on Icelandic volcanic activity during the mid-Holocene. Geology 46(1):47–50. https://doi.org/10.1130/G39633.1

Taron J, Elsworth D, Thompson G, Voight B (2007) Mechanisms for rainfall-concurrent lava dome collapses at Soufrière Hills Volcano, 2000–2002. J Volcanol Geoth Res 160:195–209. https://doi.org/10.1016/j.jvolgeores.2006.10.003

C Textor H-F Graf M Herzog JM Oberhuber 2003 Injection of gases into the stratosphere by explosive volcanic eruptions J Geophys Res Atmos 108 https://doi.org/10.1029/2002JD002987

The Intergovernmental Panel on Climate Change (2021) IPCC, 2021: summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, et al. (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Theys N, Hedelt P, De Smedt I et al (2019) Global monitoring of volcanic SO_2 degassing with unprecedented resolution from TROPOMI onboard Sentinel-5 Precursor. Sci Rep 9:2643. https://doi.org/10.1038/s41598-019-39279-y

Timmreck C (2012) Modeling the climatic effects of large explosive volcanic eruptions. Wires Clim Change 3:545–564. https://doi.org/10.1002/wcc.192

Tolstoy M (2015) Mid-ocean ridge eruptions as a climate valve. Geophys Res Lett 42:1346–1351. https://doi.org/10.1002/2014GL063015

Tost M, Cronin SJ (2016) Climate influence on volcano edifice stability and fluvial landscape evolution surrounding Mount Ruapehu, New Zealand. Geomorphology 262:77–90

Van Eaton AR, Muirhead JD, Wilson CJN, Cimarelli C (2012) Growth of volcanic ash aggregates in the presence of liquid water and ice: an experimental approach. Bull Volcanol 74:1963–1984. https://doi.org/10.1007/s00445-012-0634-9

Velicogna, I., Mohajerani, Y., A, G., Landerer, F., Mouginot, J., Noel, B., et al. (2020). Continuity of ice sheet mass loss in Greenland and Antarctica from the GRACE and GRACE Follow-On missions. Geophys Res Lett 47, e2020GL087291. https://doi.org/10.1029/2020GL087291

Violette S, Marsily GD, Carbonnel JP et al (2001) Can rainfall trigger volcanic eruptions? A mechanical stress model of an active volcano: 'Piton de la Fournaise', Reunion Island. Terra Nova 13:18–24. https://doi.org/10.1046/j.1365-3121.2001.00297.x

Walcott RI (1972) Past sea levels, eustasy and deformation of the earth. Quatern Res 2:1–14. https://doi.org/10.1016/0033-5894(72)90001-4

Watt SFL, Pyle DM, Mather TA (2013) The volcanic response to deglaciation: evidence from glaciated arcs and a reassessment of global eruption records. Earth Sci Rev 122:77–102. https://doi.org/10.1016/j.earscirev.2013.03.007

Yamasato H, Kitagawa S, Komiya M (1998) Effect of rainfall on dacitic lava dome collapse at Unzen volcano, Japan. Pap Meteorol Geophys 48:73–78. https://doi.org/10.2467/mripapers.48.73

Zanchettin D, Khodri M, Timmreck C et al (2016) The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): experimental design and forcing input data for CMIP6. Geosci Model Develop 9:2701–2719. https://doi.org/10.5194/gmd-9-2701-2016

Zhou C, Zelinka MD, Dessler AE, Wang M (2021) Greater committed warming after accounting for the pattern effect. Nat Clim Chang 11:132–136. https://doi.org/10.1038/s41558-020-00955-x

Zhu Y, Toon OB, Jensen EJ et al (2020) Persisting volcanic ash particles impact stratospheric SO_2 lifetime and aerosol optical properties. Nat Commun 11:4526. https://doi.org/10.1038/s41467-020-18352-5