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

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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 will contribute to boost research on climate-volcano impacts. Important mechanisms remain to be explored, such as how changes in atmospheric circulation and precipitation will affect the volcanic ash lifecycle. 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

Declarations

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The authors declare no competing interests.

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Authors' contributions

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Consent to participate

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I- 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., 2021, this issue). The mirror question, how climate change affects volcanic eruptions and associated 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 highlight progress made over the last two decades in understanding climate-volcano impacts (Section II), and discuss opportunities and challenges for the next decade (Section III). Section II is organised 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 categorize 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 confidence levels are based on our own judgement rather than on quantitative analysis.

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

II.1 - Climate-volcano impacts affecting pre-eruptive processes

Fig. 1 gives an overview of climate-volcano impacts that affect pre-eruptive processes. Variations in load distribution at 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 at depth in the crust and upper mantle - including pressure, deviatoric stresses, and stress orientation - with the potential to influence magma production, transport, and eruption (e.g. Mason et al. 2004) and hence affect Earth's volcanism.

The unloading effects of ice cap melt and glacial retreat are controlled by the spatial coverage of ice, the thickness of the underlying crust, and the magnitude of ice loss, and moderated by the rheology of the crust and mantle (Jull and McKenzie, 1996). Volcanic eruption rates in Iceland were several times higher at the beginning of the deglaciation following the Last Glacial Maximum than at present (Maclennan et al., 2002; Sinton et al., 2005), echoing regional and global trends in eruption rates observed in other records (e.g. Nowell et al., 2006; Huybers and Langmuir, 2009) *[well understood]*. This phenomenon may be less pronounced for arc systems (Watt et al, 2013), but there is evidence that arc volcanoes show post-glacial modulations in eruption rate and composition (e.g. Nowell et al., 2006; Rawson et al., 2016). Thermo-mechanical modelling demonstrates that ice-related stress variations may impact magma production at depth (e.g. Jull & MacKenzie, 1996) *[well understood]*, magma transport towards the surface (e.g. Michaut and Pinel, 2018) *[well understood]*, and the stability of crustal magma storage zones (Sigmundsson et al., 2010, Sigmundsson et al, 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]*, plumbing system development (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. Capra, 2006) [*well understood*]. We note that flank instability can be viewed as both a pre- and syn-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*].

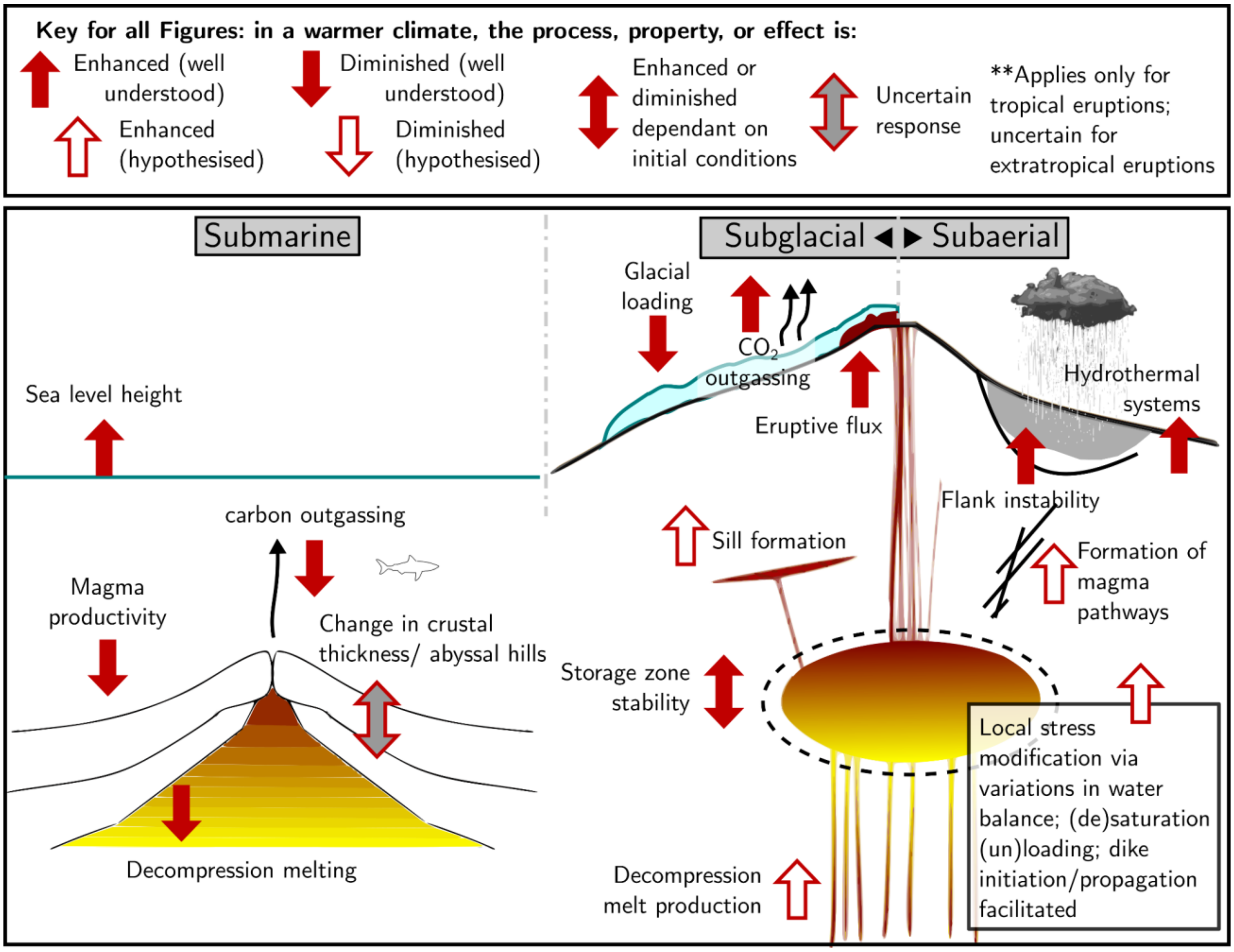

***Fig. 1** Schematics illustrating climate-volcano impacts associated with pre-eruptive processes (Section II.1) and how they are expected to unfold in the context of a warming climate.*

II.2 - Climate-volcano impacts affecting syn-eruptive processes

Fig. 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 behavior 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., under review). 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), and modifies the life cycle of sulphate aerosols (LeGrande et al., 2016; Zhu et al., 2020). Despite observation in unprecedented detail of hydrovolcanic processes from recent eruptions (e.g. Magnusson et al., 2012; Prata et al., 2017; Lopez et al., 2020; Gouhier and Paris, 2019), a comprehensive assessment of links between observed hydrovolcanic events and the fate of volcanic SO$_2$ remains to be completed.

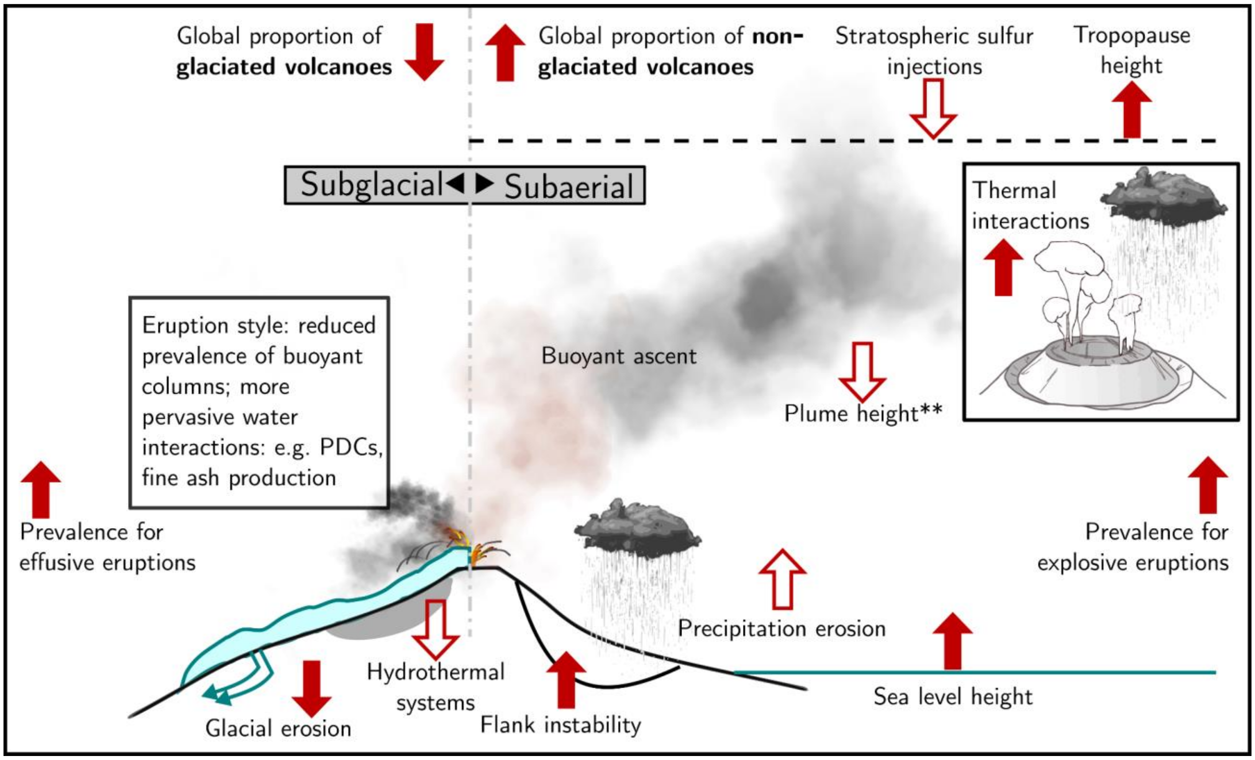

***Fig. 2**: Same as Fig. 1 but for climate-volcano impacts affecting syn-eruptive processes. See Fig. 1 for legend.*

II.3 - Climate-volcano impacts affecting post-eruptive processes

Climate-volcano impacts affecting post-eruptive processes are summarized on Fig. 3. Existing studies have focused on the life cycle and climatic impacts of volcanic sulfate aerosols. Due to the current abundance of anthropogenic 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 II.2) 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 geoengineering 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]*.

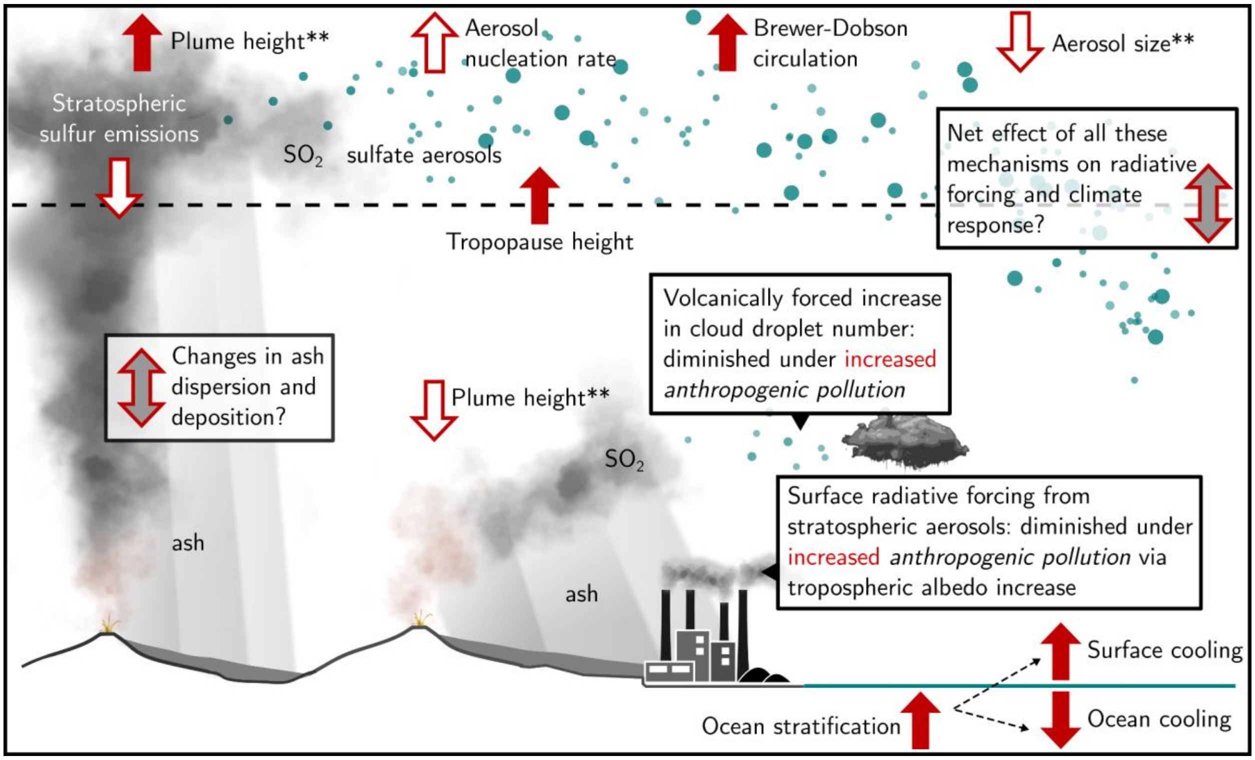

Fig. 3: *Same as Fig. 1 but for climate-volcano impacts affecting post-eruptive processes. See Fig. 1 for legend.*

III- Progresses 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 via which climate affects volcanic systems, as well as of how climate-volcano impacts played out in the past. Better spatio-temporal coverage and resolution of spaceborne observations of precipitation and ice mass (e.g. Dussaillant et al., 2019) 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. 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; 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. IVESPA, Aubry et al. 2021b) and will advance our understanding of, e.g., 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., under review, 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 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 (Section II.2) 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 remobilization 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.

IV - 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, the acceleration of the Brewer-Dobson circulation, or more frequent and intense extreme precipitation events. Such projections highlight the urgency to gain a comprehensive understanding of climate change impacts on the Earth System, including volcanic systems. *Climate-volcano impacts* remain a niche topic but could have critical implications for future volcanic hazard management and *climate-volcano feedback* loops. Understanding these implications will require interdisciplinary and holistic approaches, and close collaboration between climate scientists and volcanologists. A future involvement of social scientists and disaster risk managers may also be required as future demographic and societal evolution will modulate volcanic risk, e.g. sea-level rise may displace population living on volcanic islands closer to active volcanic vents.

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