Bulletin of Volcanology (2022) 84: 54
https://doi.org/10.1007/s00445-022-01559-3

PERSPECTIVES

Volcanic effects on climate: recent advances and future avenues

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Received: 13 October 2021 / Accepted: 18 March 2022 / Published online: 4 May 2022

Abstract

Volcanic eruptions have long been studied for their wide range of climatic effects. Although global-scale climatic impacts following the formation of stratospheric sulfate aerosol are well understood, many aspects of the evolution of the early volcanic aerosol cloud and regional impacts are uncertain. In the last twenty years, several advances have been made, mainly due to improved satellite measurements and observations enabling the effects of small-magnitude eruptions to be quantified, new proxy reconstructions used to investigate the impact of past eruptions, and state-of-the-art aerosol-climate modelling that has led to new insights on how volcanic eruptions affect the climate. Looking to the future, knowledge gaps include the role of co-emissions in volcanic plumes, the impact of eruptions on tropical hydroclimate and Northern Hemisphere winter climate, and the role of eruptions in long-term climate change. Future model development, dedicated model intercomparison projects, interdisciplinary collaborations, and the application of advanced statistical techniques will facilitate more complex and detailed studies. Ensuring that the next large-magnitude explosive eruption is well observed will be critical in providing invaluable observations that will bridge remaining gaps in our understanding.

Keywords Volcanic eruptions · Stratospheric aerosols · Aerosol-climate modelling · Climate

Introduction

Volcanic eruptions have been the most important natural cause of climate change for millennia (e.g. Hegerl et al. 2003; Schurer et al. 2013; 2014), and understanding their impact on climate is vital for investigating how the climate responds to an external forcing and for predicting future volcanic impacts that may influence society (e.g. Gao et al. 2021a; Huhtamaa et al. 2021; Raible et al. 2016; Toohey et al. 2016). The fundamentals of how eruptions impact the climate are well-established: sulfur dioxide (SO_2) emitted during an eruption forms sulfate aerosol that scatters incoming solar radiation, causing a negative radiative forcing. If SO_2 is injected into the stratosphere, where the aerosol can reside for several years, the eruption can lead to a significant

Editorial responsibility: J.H. Fink

This paper constitutes part of a topical collection:

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

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decrease in surface insolation and produce surface cooling (e.g. Dutton and Christy 1992; McCormick et al. 1995; Robock and Mao 1995). Sulfate aerosol also absorbs infrared radiation that can lead to a heating of the stratosphere (e.g. Labitzke and McCormick 1992; Stenchikov et al. 1998; Young et al. 1994). Both the cooling and heating effects lead to a cascade of further impacts. The cooling can reduce precipitation and ocean heat content, the heating can change circulation in the atmosphere, and the volcanic aerosol itself can impact atmospheric chemistry leading to ozone depletion (see Robock 2000 for a review). A summary of climate impacts arising from large-magnitude eruptions (defined here as explosive eruptions with injections of more than 5 Tg of SO_2 into the stratosphere) is shown in Fig. 1. However, the intricacies of these wider impacts are less well understood than the overall impact on radiation and surface temperature, owing to a lack of observations following large-magnitude eruptions. Most of our knowledge stems from observations of the 1991 eruption of Mt. Pinatubo, the most recent large-magnitude eruption to have occurred. In addition, differences in the results from different climate models and discrepancies between simulated and observed or reconstructed responses indicate that our understanding is far from complete (e.g. Chylek et al. 2020; Clyne et al. 2021; Pauling et al. 2021; Tejedor et al. 2021a, b; Wilson et al. 2016; see Zanchettin et al. 2016 for a review).

Observations, proxy reconstructions and modelling of volcanic eruption climate effects: advances over the last twenty years

Numerous advances in the field of volcanic effects on climate have been made in the last twenty years despite the absence of a large-magnitude eruption. We now have comprehensive datasets of volcanic SO_2, sulfate aerosol and aerosol extinction from ground-based, balloon and satellite measurements (e.g. Carn et al. 2016; Kremser et al. 2016; von Savigny et al. 2020). These data provide much better constraint on volcanic emissions and include daily and near-global observations that show where SO_2 and aerosol are dispersed. Improvements in the algorithms used in satellite retrievals have also

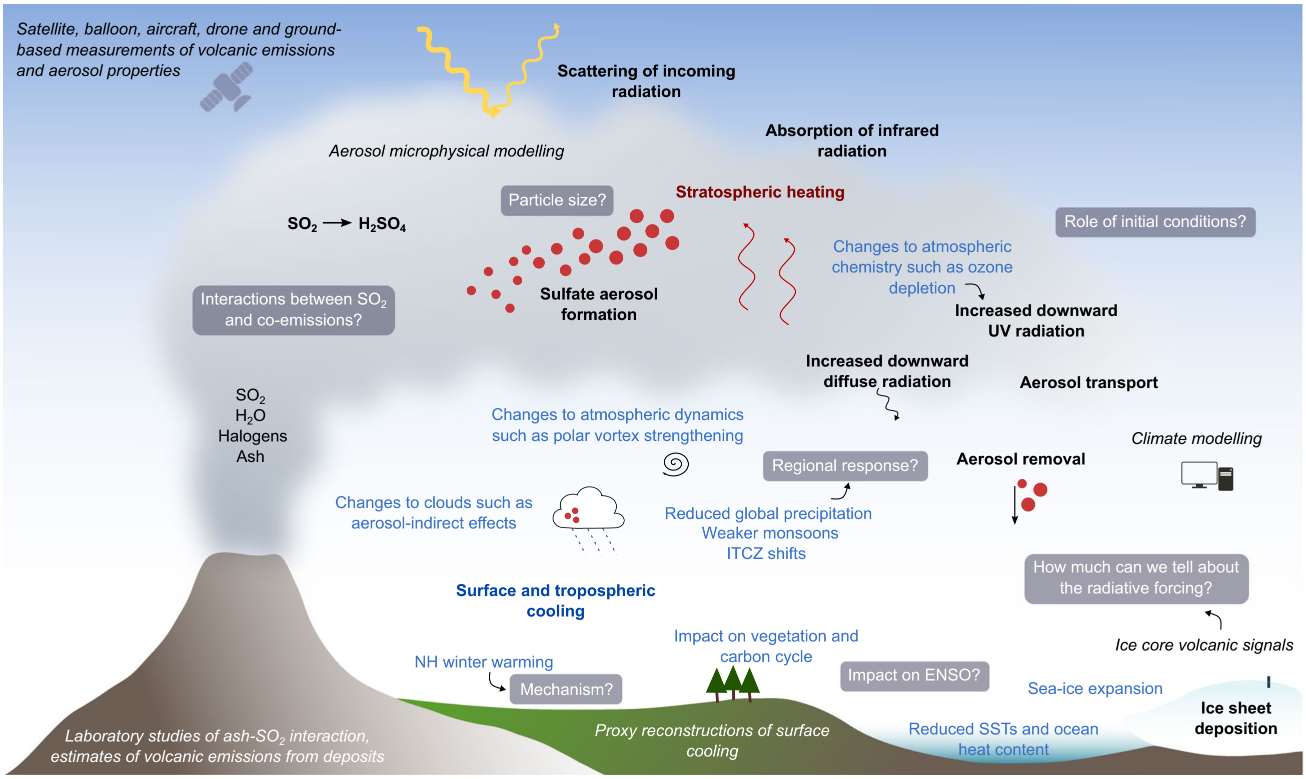

Fig. 1 Summary of major climate impacts following a large-magnitude eruption and the processes that produce them, updated from Timmreck (2012). Processes are in bold, climate impacts in blue. Italic text outlines the methods used to understand volcanic-climate impacts (observations, proxy reconstructions and modelling). Key outstanding research questions are shown in boxes. SST is sea surface temperature, ITCZ is Intertropical Convergence Zone and ENSO is El Niño Southern Oscillation. Review papers since that of Robock (2000) include those by Cole-Dai (2010) (ice core focus), Timmreck (2012) (climate modelling focus), Kremser et al. (2016) (non-volcanic and volcanic stratospheric aerosol) and Swingedouw et al. (2017) (explosive eruptions and modes of variability). A collection of highlights on the topic of volcanoes and climate can be found in the 2015 Past Global Changes (PAGES) magazine (LeGrande et al. 2015)

enabled revised estimates of the emissions of past eruptions, for example those of the 1991 Mt. Pinatubo eruption (Carn 2021; Fisher et al. 2019). A notable advance has been the development of the Global Space-based Stratospheric Aerosol Climatology (GloSSAC) (Kovilakam et al. 2020; Thomason et al. 2018), which is a continuous record of stratospheric aerosol optical properties from 1979 to 2018. We have observed a minimum in stratospheric aerosol from 1998 to 2000, and in the years following, observations have demonstrated that stratospheric aerosol variability has been dominated by small-magnitude (< 5 Tg SO_2) eruptions (Solomon et al. 2011; Vernier et al. 2011), which have also been important in offsetting some anthropogenic greenhouse gas forcing (e.g. Monerie et al. 2017; Ridley et al. 2014; Santer et al. 2014; 2015; Schmidt et al. 2018). The recognition that, together, small-magnitude eruptions are important for climatic perturbations is a shift from the traditional idea that it is only the large stratospheric-injecting events that matter for climate (although these do have much larger impacts per eruption). Observations, as well as aerosol modelling, in particular following the 2014–2015 Holuhraun eruption in Iceland, have also shown that eruptions that emit gases mainly into the troposphere can increase the reflectivity of clouds through an aerosol interaction known as the aerosol-indirect effect. This causes an additional radiative forcing of climate (e.g. Gettelman et al. 2015; Malavelle et al. 2017; McCoy and Hartmann 2015; Schmidt et al. 2010; 2012).

Reconstructions of past temperature variability and of past volcanic radiative forcing have also improved, revealing more details about large historic eruptions and their potential impacts (Sigl et al. 2015). Peaks in sulfate concentrations in ice cores have been used for many years to identify the occurrence of eruptions, as some of the volcanic sulfate aerosol is eventually deposited on the ice sheets and preserved in the ice (Fig. 1). The ice core sulfate concentrations are used to estimate the amount of sulfur that was injected into the atmosphere and the potential impact on climate (Arfeuille et al. 2014; Crowley and Unterman 2013; Gao et al. 2008). Several new, long and seasonally to annually resolved ice core records of volcanic sulfate (Cole-Dai 2010; Sigl et al. 2015) have thus helped to clarify the history and climate forcing of past volcanic eruptions. New reconstructions provide estimates of stratospheric SO_2 emissions, eruption latitudes and the stratospheric aerosol optical depth for eruptions over the last 2500 years (Toohey and Sigl 2017) to 10,000 years (Sigl et al. 2022). These reconstructions provide considerable updates to previous reconstructions which had large uncertainties and discrepancies in terms of dates and magnitudes for some eruptions (Jungclaus et al. 2017). Volcanic emissions and forcing reconstructions are important because they are needed as input to climate model simulations and for comparison with reconstructions of past temperature (e.g. Jungclaus et al. 2017; Sigl et al. 2015; Timmreck et al. 2021; Wilson et al. 2016). New large-scale tree-ring reconstructions of Northern Hemisphere (NH) surface temperature that better capture rapid temperature changes, and which are less prone to long-term memory effects, have shown the dominant role that volcanic eruptions exerted over preindustrial climate variability (e.g. Anchukaitis et al. 2017; Büntgen et al. 2021; King et al. 2021; Schneider et al. 2017; Wilson et al. 2016).

Climate model simulations of volcanic eruptions have evolved considerably in the last twenty years (Timmreck 2012; Timmreck et al. 2018). Climate models have higher spatial resolutions, allowing regional impacts to be better captured. They are also more complex, including more processes such as interactive chemistry and aerosol microphysics. As a result, simulating the effects of volcanic eruptions has evolved from simply turning down the magnitude of the incoming solar radiation to mimic the effects of volcanic aerosol (e.g. Bauer et al. 2003; Peng et al. 2010; Yoshimori et al. 2005), to prescribing aerosol properties (e.g. Ammann et al. 2003; Eyring et al. 2013; Gao et al. 2008), to simulating eruptions from an initial emission of SO_2 (e.g. 2006 Mills et al. 2016; SPARC 2006; Timmreck et al. 2018). Improved datasets of volcanic aerosol properties allow eruptions to be better represented in models that: 1) do not have complex aerosol schemes or choose not to use them because of computational cost or 2) prescribe the aerosol properties to be fully consistent with observations and to ensure that the radiative forcing from eruptions is consistent with other models (Zanchettin et al. 2016; 2022). Improved volcanic aerosol forcing datasets that include revised estimates of the post-Pinatubo period and the effects of small-magnitude eruptions have led to better matches between observations and model output of recent surface and tropospheric temperatures trends (e.g. Haywood et al. 2014; Fyfe et al. 2013; 2021; Santer et al. 2014) and of stratospheric warming after the 1991 Mt. Pinatubo eruption (e.g. Arfeuille et al. 2013; Revell et al. 2017; Rieger et al. 2020).

Global climate models with stratospheric aerosol microphysical schemes simulate the aerosol lifecycle. This includes the conversion of SO_2 to sulphuric acid vapour, the formation (nucleation) and growth (through condensation and coagulation) of sulfate aerosol, its atmospheric transport, chemical and radiative interactions and deposition (Kremser et al. 2016). These models allow volcanic eruptions to be simulated with greater realism and for the effects of changing the eruption source parameters to be easily explored. Studies have demonstrated that the specific climatic impact is dependent on the emission magnitude, eruption season, altitude of emission and latitude of the volcano (e.g. Arfeuille et al. 2014; Marshall et al. 2019; Metzner et al. 2014; Stoffel et al. 2015; Toohey et al. 2011; 2019). Aerosol-climate modelling studies have also demonstrated the importance of aerosol growth in limiting the climate response as larger particles are less efficient at scattering radiation and fall out of the atmosphere more quickly than smaller particles (e.g. Arfeuille et al. 2014; English et al. 2013; Pinto et al. 1989; Timmreck et al. 2010). Accounting for aerosol growth subsequently reduces the surface temperature response following large-magnitude eruptions and has resulted in better agreement between simulated cooling and that reconstructed from tree rings for some large eruptions in the last millennium (Stoffel et al. 2015). Aerosol-climate modelling studies have also shown the importance of stratospheric heating due to absorption of infrared radiation by sulfate aerosol, as well as by ash and SO_2, for lofting aerosol and its subsequent dispersion (e.g. Aquila et al. 2012; Muser et al. 2020; Niemeier et al. 2021; Pitari et al. 2016; Sekiya et al. 2016; Stenchikov et al. 2021).

Novel techniques, such as statistical emulation, have also been applied to aerosol-climate model simulations (Marshall et al. 2019). Statistical emulators can be used to understand how uncertainties in model inputs, in this case different eruption source parameters, can change the model output, such as the radiative forcing caused by an eruption. These emulators replace the model and can be used to make predictions of what the climate impact may be for any given eruption, even if it has not been simulated directly with the model. An example of an emulator surface that predicts the radiative forcing from explosive eruptions occurring at different latitudes and with different SO_2 emissions is shown in Fig. 2.

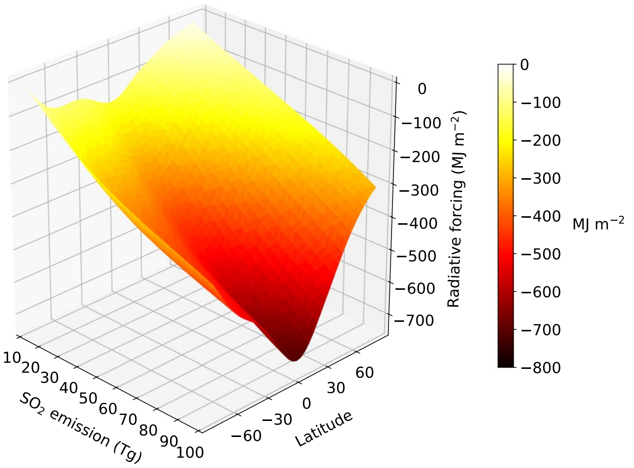

Fig. 2 Time-integrated volcanic radiative forcing over three years (in MJ m^{-2}) as a function of eruption latitude and SO_2 emission (in Tg of SO_2) as predicted by a Gaussian process emulator trained from aerosol-climate simulations of a wide range of explosive eruptions (modified from Marshall et al. 2019). The emulator allows radiative forcing to be predicted for a wide range of eruptions that were not explicitly simulated and which can be evaluated in a fraction of the time taken to run a climate model simulation

Summary of climate impacts

Over the past two decades, observations, proxies and modelling have, together, led to a better understanding of the wide range of volcano-climate impacts as outlined in Fig. 1. Impacts include:

- Changes to atmospheric dynamics (e.g. DallaSanta et al. 2019; Diallo et al. 2017; Toohey et al. 2014; Bittner et al. 2016b) including NH winter warming (e.g. Bittner et al. 2016a; Coupe and Robock 2021; Zambri and Robock 2016; Zambri et al. 2017)
- Ozone depletion (e.g. Brenna et al. 2019; Dhomse et al. 2015; Klobas et al. 2017; Ming et al. 2020; Solomon et al. 2016)
- A reduction in precipitation (e.g. Iles et al. 2013; Man et al. 2021; Stevenson et al. 2016; Trenberth and Dai 2007)
- Weaker monsoons (e.g. Fadnavis et al. 2021; Liu et al. 2016; Man et al. 2014; Paik et al. 2020; Zhuo et al. 2021)
- Reduced ocean heat content (e.g. Church et al. 2005; Dogar et al. 2020; Gleckler et al. 2006; 2016; Gupta and Marshall 2018)
- Shifts in the position of the Intertropical Convergence Zone (ITCZ) (e.g. Colose et al. 2016; Erez and Adam 2021; Haywood et al. 2013; Iles and Hegerl 2014; Ridley et al. 2015)
- Increased sea ice (e.g. Miller et al. 2012; Gagné et al. 2017; Pauling et al. 2021; Zanchettin et al. 2014)
- Shifts in phases of modes of climate variability (see Swingedouw et al. 2017 for a review) including the North Atlantic Oscillation (e.g. Hermanson et al. 2020; Sjolte et al. 2021; Zanchettin et al. 2013) and the El Niño Southern Oscillation (ENSO) (e.g. Khodri et al. 2017; McGregor et al. 2020; Pausata et al. 2020; Predybaylo et al. 2020; Stevenson et al. 2016)
- Changes to Atlantic Meridional Overturning Circulation and Atlantic Multidecadal Variability (e.g. Fang et al. 2021; Mann et al. 2021; Ménégoz et al. 2018; Pausata et al. 2015; Waite et al. 2020)
- Disruption to the Quasi-Biennial Oscillation (Brenna et al. 2021; DallaSanta et al. 2021)
- Changes to the carbon cycle (e.g. Delmelle et al. 2015; Eddebbar et al. 2019; Foley et al. 2014; Frölicher et al. 2011)

Studies have demonstrated that, following eruptions, adjustments in atmospheric temperature and constituents, such as clouds and stratospheric water vapour, lead to additional radiative effects that alter the overall volcanic forcing (e.g. Gregory et al. 2016; Marshall et al. 2020; Schmidt et al. 2018). Co-emissions of halogens are important for catalysing ozone depletion, which leads to stratospheric cooling that alters both the radiative balance and aerosol size, further impacting the radiative forcing (Staunton-Sykes et al. 2021). Kroll et al. (2021) demonstrated that indirect increases in stratospheric water vapour following eruptions, which affects the radiative budget, depends on the eruption magnitude, the shape of the aerosol layer and its height with respect to the tropopause.

In addition to the recognition that small-magnitude eruptions matter for climate, high-latitude eruptions have also been shown to be more important than previously thought. Analysis of volcanic SO_2 emission reconstructions, tree-ring temperature reconstructions and aerosol-climate model simulations suggest that large high-latitude eruptions can significantly impact NH climate, producing stronger hemispheric cooling than tropical eruptions of the same magnitude (Toohey et al. 2019).

Knowledge gaps, uncertainties and future opportunities

For many of the climate impacts listed above, the exact response such as the timing, magnitude or spatial heterogeneity often differs not only between climate model studies, but also between model-simulated and observed or reconstructed responses (e.g. Driscoll et al. 2012; Pauling et al. 2021; Wilson et al. 2016; Zanchettin et al. 2016; Zhuo et al. 2020; Zuo et al. 2021). Aerosol-climate modelling studies have also demonstrated large discrepancies in the simulated aerosol size and dispersion following past large eruptions such as the 1815 eruption of Mt. Tambora, which leads to differences in the radiative impact, and is a result of differences in the models' chemistry and aerosol schemes (Clyne et al. 2021). Here we outline some of the main knowledge gaps and research questions and suggest how they may be addressed in the future.

Processes in the volcanic cloud

Although observations of volcanic emissions have improved, uncertainties in satellite retrievals mean that it is still difficult to differentiate the components of even the best-observed volcanic clouds. This includes measurements of the magnitude and vertical distribution of SO_2, halogens, water, ash and ice, and the amount and size of sulfate aerosol particles. Accurate estimates of these properties are needed to predict the potential climate impact and are required as input to aerosol-climate models. The 1991 eruption of Mt. Pinatubo remains a benchmark simulation for climate models. However, some aerosol-climate models must inject 10 Tg of SO_2, lower than that inferred from satellite observations (~ 14–23 Tg; Guo et al. 2004), in order to best match with extinction measurements (Dhomse et al. 2014; 2020; Mills et al. 2016; 2017). This suggests that either a sink of SO_2 in the models is missing, such as scavenging by ash and ice, that the injection altitude and/or simulated lofting of the aerosol was incorrect (Stenchikov et al. 2021), or that the satellite retrievals overestimated the emission. Most of the ash produced during an eruption is short-lived in the atmosphere (Rose et al. 2001), but satellite, aircraft and balloon measurements indicate that some ash particles can remain airborne for many days to months (e.g. Mossop 1964; Pueschel et al. 1994; Vernier et al. 2016). Laboratory studies have shown that ash surfaces react with various gases and liquids such as SO_2, sulphuric acid, hydrochloric acid, hydrofluoric acid, ozone and water (e.g. Delmelle et al. 2018; Durant et al. 2008; Gutiérrez et al. 2016; Maters et al. 2017). However, the impacts of ash–SO_2 interaction, for example, on the stratospheric SO_2 lifetime and sulfur burden have only recently been demonstrated in climate modelling (Zhu et al. 2020). Outstanding questions therefore include:

- *What is the ratio of SO_2 to ash and to what extent do they separate as they disperse?*
- *How much of the SO_2 is scavenged by ash and ice and how does this impact the amount and size of sulfate aerosol and therefore the climate impact?*
- *How large do the aerosol particles grow?*

Going forward, more complex aerosol-climate models will enable the evolution of sulfate aerosol to be investigated in more detail. Examples include the addition of co-emissions, interactive photolysis where SO_2 and aerosol can affect the photolysis rates which impacts the conversion rate of SO_2 to sulfate (Osipov et al. 2020), and meteoric smoke particles, on which sulphuric acid can condense (e.g. Brooke et al. 2017; Mills et al. 2005; Saunders et al. 2012). Co-emissions of water and halogens can impact the chemical formation of the sulfate aerosol (LeGrande et al. 2016), but large uncertainties remain in the magnitudes of these emissions for past eruptions (Mather 2015) and not all models include them. Increasing experimental and observational data describing these processes, such as rates and magnitudes of SO_2 uptake by ash under various atmospherically relevant conditions (Lasne et al. 2022), present opportunities to integrate interactions involving co-emissions in modelling studies of the climate impacts of explosive eruptions. The Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP; Timmreck et al. 2018) will provide the first intercomparison of stratospheric aerosol properties amongst aerosol-climate models and proposes several standardised model experiments where results will be compared to in situ and satellite observations. Results should lead to an understanding of some of the structural and parametric uncertainties in models and how these differ between simulations of large-magnitude eruptions, such as the 1991 eruption of Mt. Pinatubo, and small-magnitude eruptions.

Ultimately, the next large-magnitude eruption that occurs will offer the opportunity for new observations, in particular of interactions between SO_2, ash, water and halogens, as well as the aerosol size distribution. Such an event will provide a new test case for climate models. Both national (Carn et al. 2021; Fischer et al. 2021) and international response initiatives (VolRes; https://wiki.earthdata.nasa.gov/display/volres) have been developed to coordinate efforts to ensure a rapid response that will enable scientists to gain invaluable observations and to assess the potential impact on climate in the immediate aftermath of the eruption.

Regional impacts

The response of the NH winter climate and the response of ENSO to a volcanic forcing is particularly uncertain. Winter warming following large tropical eruptions is mechanistically often linked to a strengthening of the NH polar vortex, but models have not always been able to capture the response (e.g. Bittner et al. 2016a; Driscoll et al. 2012; Toohey et al. 2014; see Zambri et al. 2017 for an overview), and the mechanism has been questioned (Polvani et al. 2019; Polvani and Camargo 2020), although re-supported by, for example, Azoulay et al. (2021). Coupe and Robock (2021) demonstrated that models could accurately simulate the winter warming after the eruptions of Agung in 1963, El Chichón in 1982 and Mt. Pinatubo in 1991, if they also accurately simulated the El Niño states that accompanied these eruptions. Observations and modelling suggest that El Niño events are more likely in the year following an eruption (e.g. Adams et al. 2003; Khodri et al. 2017; Stevenson et al. 2017), although models are still imperfect at capturing the response, and not all observations support the link (Dee et al. 2020, but see Robock 2020; Zhu et al. 2022).

Changes to regional precipitation and the strength of monsoons are also uncertain due to complex spatial patterns, intermodal spread, discrepancies between proxies and disagreement between model simulations and observations or proxy reconstructions (e.g. Gao and Gao 2018; Iles et al. 2013; Rao et al. 2017; Tejedor et al. 2021a). Hemispheric asymmetry in the sulfate aerosol distribution is important for the response of regional hydroclimate (e.g. Colose et al. 2016; Haywood et al. 2013; Jacobson et al. 2020; Yang et al. 2019), but the exact spatial distribution of aerosol is unknown for eruptions prior to the satellite era and therefore there are uncertainties in the volcanic forcing that some models rely upon. The response of precipitation and monsoons is also modulated by ENSO (e.g. Gao et al. 2021b; Paik et al. 2020; Singh et al. 2020). Outstanding questions include:

- *How does the combination of ENSO and the forcing from eruptions (stratospheric heating and tropospheric cooling) impact NH winter circulation?*
- *Is there a robust response of regional hydroclimate?*

Multi-decadal impacts

Closely spaced volcanic eruptions have been hypothesised to lead to sustained cooling via ocean and sea-ice feedbacks (e.g. Miller et al. 2012; Toohey et al. 2016; van Dijk et al. 2021). However, uncertainties remain regarding the role of internal variability and the dependence on the current climate state (e.g. Moreno-Chamarro et al. 2017; Schneider et al. 2009; Slawinska and Robock 2018; Zanchettin et al. 2012). An outstanding question is, thus: *Would a cluster of eruptions cause long-term cooling in today's climate, or in the future?* For a review of how climate change itself affects the climate impact of eruptions (climate-volcanic impacts), see Aubry et al. (2022, this issue).

Dedicated model intercomparison projects such as the Volcanic Forcing Model Intercomparison Project (VolMIP; Zanchettin et al. 2016), which is motivated by discrepancies between models, will be vital in improving our understanding of both regional and long-term impacts. The project defines a common volcanic forcing input and sets of initial conditions, which will account for previous uncertainties in modelling studies. Advanced statistical techniques, such as emulation, will also enable further detailed studies to explore the sensitivity of climate impacts to parameterisations in models and to the properties of the eruption, as proposed, for example, by Timmreck et al. (2018).

Reconstructing past volcanic forcing

Although reconstructions of past volcanic forcing have improved (Toohey and Sigl 2017), there is uncertainty in the conversion between volcanic sulfate deposition and the stratospheric sulfur burden, with modelling studies demonstrating that this depends on the properties of an eruption (Marshall et al. 2021; Toohey et al. 2013) and the model itself (Marshall et al. 2018). Uncertainties in past volcanic forcing underpin many model-data discrepancies (e.g. Stoffel et al. 2015; Wilson et al. 2016; Zanchettin et al. 2019). Thus, an outstanding question is: *How much can ice core sulfate records tell us about the radiative forcing, such as the magnitude, duration, and spatial structure?*

Closer connections have now been formed between modelling centres, volcanologists and observation specialists. This has been fostered by international groups such as the Volcanic Impacts on Climate and Society (VICS) PAGES working group. Multi-disciplinary studies that combine petrological, historical and climate modelling evidence have led to the attribution of previously unidentified eruptions (from sulfate spikes in ice cores) to specific volcanoes, including the 1257 eruption of Samalas (Lavigne et al. 2013) and the 43 BCE eruption of Okmok (McConnell et al. 2020). Attributing more of the unidentified eruptions to specific volcanoes will aid in improving past reconstructions. Improvements in the techniques used to measure sulfur isotopes in ice cores have also been made, which can indicate whether the sulfur emissions were injected into the troposphere or the stratosphere (e.g. Baroni et al. 2008; Burke et al. 2019; Savarino et al. 2003b). Further aerosol-climate modelling studies to investigate the relationship between sulfate deposition and the radiative forcing, additional ice core records, analyses of sulfur as well as oxygen isotopes (e.g. Gautier et al. 2019; Martin 2018; Savarino et al. 2003a), and more proxy reconstructions especially from the Southern Hemisphere where few records are currently available, will tell us more about these past eruptions and their climate impact.

Conclusions

Research into volcanic effects on the climate has evolved considerably over the last twenty years even in the absence of a large-magnitude eruption. We have better observations of eruptions, better proxy records of temperature changes, better reconstructions of past volcanic forcing from ice core records and state-of-the-art aerosol-climate models that allow eruptions to be simulated in greater detail and uncertainties to be explored. Ultimately, advances will be made following observations and modelling of the next large (≥ 5 Tg SO_2) eruption, from dedicated model intercomparison projects (VolMIP and ISA-MIP), as well as from interdisciplinary studies and collaborations between atmospheric scientists, climate modellers, volcanologists and historians. At the time of writing, we are just beginning to see the impact from the January 2022 eruption of Hunga Tonga-Hunga Ha'apai, the first explosive eruption since Mt. Pinatubo in 1991 to be observed by satellites where material has been injected to extremely high levels in the stratosphere (> 30 km). Although initial estimates of the SO_2 emission are too low (~ 0.4 Tg, https://so2.gsfc.nasa.gov/omps_2012_now.html#hunga, last accessed 28/1/22) to cause global cooling, we anticipate that this eruption will be the focus of many studies to come, especially in understanding interactions between ash, water, ice, halogens and sulfur in the volcanic plume, and impacts on regional weather.

Acknowledgements The authors would like to thank Thomas Aubry for insightful discussions and comments, and an anonymous reviewer, Mark Jellinek and Andrew Harris for their reviews, which have greatly improved this manuscript. LM and AS were funded by the Natural Environment Research Council (NERC) grant VOL-CLIM (NE/S000887/1). AS was also funded by NERC grant NE/S00436X/1 (V-PLUS). CT was funded from the Deutsche Forschungsgemeinschaft Research Unit VolImpact (FOR2820, Grant No. 398006378). AR was funded by U.S. National Science Foundation grant AGS-2017113. EM benefits from an Early Career Fellowship funded jointly by the Leverhulme Trust and Isaac Newton Trust. The authors acknowledge the important role that various activities have played in fostering interdisciplinary research on volcanoes and climate, including: the Volcanic Impacts on Climate and Society (VICS) working group of the Past Global Changes (PAGES) project, the Model Intercomparison Project on the climate response to Volcanic forcing (VolMIP) and the Stratospheric Sulfur and its Role in Climate (SSiRC) activity.

Author contributions LM and AS formulated the initial proposal, with revisions from all authors. LM wrote the initial draft. EM and CT wrote parts of the manuscript, and AS, AR and MT substantially reviewed and edited the manuscript.

Declarations

Competing Interests The authors declare no competing interests.

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