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Volcanic Eruptions: A Source of Irreducible Uncertainty for Future Climates

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Key Points:

- The study by Man Mei Chim and Colleagues shows that volcanic forcing can strongly affect future climate projections
- The study reaffirms the importance of natural variability for future climates, stimulating research on volcano-climate interactions
- Volcanic forcing remains unpredictable, which rises the question of how to communicate irreducible climate projection uncertainties

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Abstract Volcanic forcing, a major natural source of climate variability, represents a challenge for current climate modeling because of the unpredictability and specificity of individual eruptions, and because of the complexity of processes linking the eruption to the climate response. Volcanic forcing is largely underrepresented in available future climate projections, which is a critical problem. The study by Man Mei Chim and Colleagues (Chim et al., 2023, https://doi.org/10.1029/2023GL103743) tackles this known unknown and reveals how climatically relevant volcanic activity may be stronger than currently thought in a future warmer climate, enhancing uncertainty of climate projections. The study exemplifies the profound implications of inaccuracies within simplified climate scenarios and motivates new research on volcanically forced climate variability. It also arouses some thoughts on climate uncertainty communication.

Plain Language Summary Volcanic eruptions are a critical part of the earth system, capable of causing large climatic fluctuations over periods from years to decades. Available scenario experiments typically neglect volcanic forcing, which may cause systematic errors in future climate projections. Man Mei Chim and Colleagues (Chim et al., 2023, https://doi.org/10.1029/2023GL103743) use a series of statistical and mathematical models to comprehensively simulate how volcanic eruptions may affect climate during the 21st century. The results indicate that a more realistic representation of volcanic eruptions yields slightly less future warming and larger uncertainty than standard projections. In other words, we are less confident of future climate changes once we account for the (unpredictable) volcanic forcing. By considering future volcano-climate interactions in their whole complexity and revealing a substantial role for small-to-moderate eruptions, the study places a new important piece in the volcano-climate puzzle. It will motivate new coordinated research to improve the simulated representation of volcano-climate interactions not only in the ambit of future climate scenarios but in paleoclimatic investigations and idealized volcanic experiments well. The research also reminds us of limitations inherent in climate model experiments and should foster improved communication of natural climate variability and associated uncertainties.

1. Main Text

Volcanic eruptions are the source of a major natural forcing of Earth's climate: The stratospheric sulfate aerosol layer is temporarily enhanced after major explosive eruptions, reducing the amount of incoming solar radiation reaching the planet's surface, which has a global cooling effect. Volcanic eruptions are episodic, irregular, potentially disastrous, and unpredictable, and so is volcanic forcing. Unraveling the volcano-climate connection is not only a great endeavor but also a challenge for climate scientists.

A glance at radiative forcing during the historical period already illustrates that volcanic eruptions stand out among other forcing agents (Figure 1): The apparently random succession of volcanic negative spikes of different amplitude contrasts with the progressive evolution of other natural and anthropogenic forcings. The radiative effect of volcanic aerosols can be so strong that for large events it temporarily dominates the Earth's energy budget. For instance, aerosol from the 1991 Pinatubo eruption offset, at its peak, the total net radiative forcing by all other agents, in a period when it was otherwise shaped by anthropogenic greenhouse gas emissions. Grand events, such as the early 19th-century cluster of large volcanic eruptions, including the 1809 unidentified and 1815 Tambora eruptions, can produce a peak negative forcing around or even exceeding in absolute value the (more persistent) positive forcing estimated for a doubling of atmospheric CO_2 concentration (~3.8 W/m^2). Grand eruptions can lead in their aftermath to a global-average surface cooling over landmasses of more than 1°C and strongly affect decadal and interdecadal climate variability (Figure 1). These are rare events (just a few over a thousand years) and remain in many aspects enigmatic: They still engage paleoclimatologists and climate

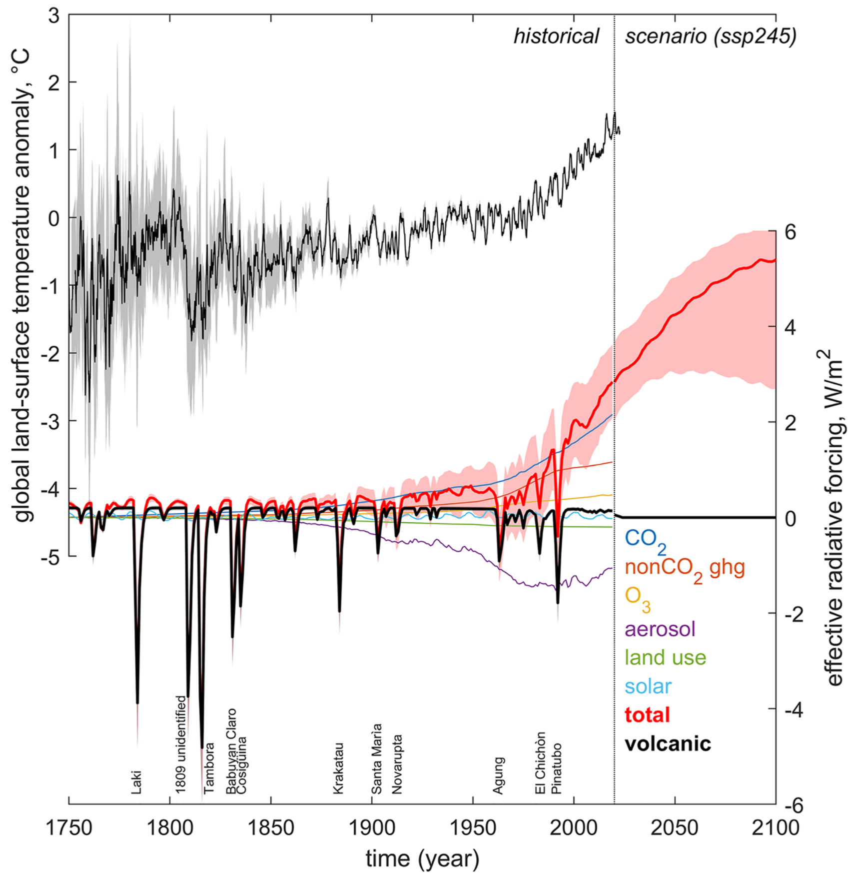

Figure 1. Top: Estimated annual-average global land-surface average temperature based on the Complete Berkeley Data set (Rohde & Hausfather, 2020). Bottom: total and single-agent effective radiative forcing estimated from coupled model intercomparison project *historical* and, for total and volcanic forcing, the *ssp245* scenario simulations (Forster et al., 2021). Shading illustrates the uncertainty range for selected variables (95% confidence interval for temperature and 5–95 percentile range for effective radiative forcing). Major volcanic eruptions are reported at the bottom. Note the lack of volcanic eruptions in the scenario period, the critical problem addressed by CHIM23.

modelers in efforts to understand and reconcile apparent inconsistencies between reconstructions and simulations (Timmreck et al., 2021) and across model results (Zanchettin et al., 2016). Less striking for interannual climate variability but equally important for decadal and interdecadal trends are clusters of small-to-moderate eruptions, such as the early 21st-century cluster that some studies invoked as an explanation of the hiatus (a temporary slowdown) in the rise of global-mean surface temperature during the same period (Santer et al., 2014).

With this premise of outstanding evidence acquired in the past decades of the relevance of volcanic eruptions for climate, it is surprising how underrepresented volcanic forcing is in climate projections, with only a few studies having so far investigated volcanoes in a warmer climate. Figure 1 illustrates the striking discrepancy in the complexity of volcanic and hence total radiative forcing in historical and scenario experiments contributing to the sixth phase of the coupled model intercomparison project (CMIP6). There is no actual eruption in the scenario experiments, but a constant volcanic forcing generated by prescribed constant volcanic aerosol optical properties derived from data for the historical period (see also Cross-Chapter Box 4.1 in Lee et al., 2021). In practice, volcanic forcing is neglected in current climate projections.

The paper by Man Mei Chim and Colleagues (Chim et al., 2023, hereafter CHIM23) is a much-needed step forward toward tackling this known unknown. Especially, their comprehensive approach allows for an unprecedented level of complexity in the description of volcanic forcing in a warmer climate, including potential effects of climate change on volcanic plume dynamics and aerosol life cycle, the so-called climate-volcano feedback (Aubry et al., 2019, 2021).

The heart of the matter is that individual eruptions are unpredictable. But, history allows the generation of "stochastic eruption scenarios" where the statistical properties of a sequence of documented events, such as the frequency of occurrence of events with certain magnitude, is used to produce synthetic yet possible sequences of volcanic eruptions. This method is at the forefront of climate research, as the first attempt in this regard dates back to just a few years ago (Bethke et al., 2017). The key to build realistic stochastic eruption scenarios are reliable volcanic histories, mainly derived from analysis of volcanic aerosol depositions in ice cores. As there is continued refinements to the synchronization and dating of ice-core records, and to the methods used to estimate volcanic stratospheric sulfur injections from depositions, volcanic histories have improved through time (e.g., Burke et al., 2019; Crowley & Unterman, 2013; Sigl et al., 2015, 2022). Still, they remain subject to uncertainties and limitations regarding the detection of individual events and their characteristics, such as magnitude, timing and location. For instance, in ice-sheet archives discriminating volcanic events from the noisy background of aerosol depositions from other sources becomes increasingly difficult for decreasing eruption magnitude (Toohey & Sigl, 2017). Missing small to moderate eruptions means that volcanic histories from ice-core records are biased toward reduced volcanic activity and forcing, and so are scenarios based solely on such data. CHIM23 accounts for this potential bias by sampling small events from the satellite period only, when they are well observed. The study provides compelling evidence that including small volcanic eruptions leads to significantly more sulfur injections in the stratosphere till the end of the 21st century, hence more climatically relevant aerosol, compared to what currently assumed in CMIP6 scenarios. Of course, here a critical assumption concerns the representativeness of the 40-years satellite record for long-term statistics of small eruptions.

Stochastic scenarios for large eruptions in CHIM23 build on a recent data set of volcanic aerosol depositions in ice cores covering the past 11,500 years (Sigl et al., 2022). Climatically relevant volcanic parameters from this record can vary across centuries by even more than an order of magnitude, revealing a very large potential uncertainty in volcanic forcing during the 21st century. In fact, there might be even more diversity and complexity in volcanic eruptions, hence uncertainty in 21st century volcanic forcing, than indicated by this nonetheless impressive Holocene database. Nature is an endless source of new discoveries, and the Hunga Tonga submarine eruption in 2022 revealed a previously unobserved type of large explosive volcanic event, where the amount of water vapor injected into the stratosphere largely dominates that of sulfur gases. As water vapor is a potent greenhouse gas, its positive radiative forcing overwhelmed the aerosol negative forcing causing the first post-eruption surface warming in the observational record (Sellitto et al., 2022). Our grasp on events like the Hunga Tonga in the past is weak at best, hence providing further uncertainty to volcanic scenarios.

The comprehensive stochastic eruption scenarios are a potential breakthrough for climate projections. With a more realistic implementation of volcanic activity, the model results change significantly and pervasively across climate compartments. CHIM23 is thus very effective in illustrating the potential shortcomings for our representation of future climates when key aspects of the earth system are underrepresented or oversimplified in scenario simulations. For instance, surface cooling after major eruptions can significantly dampen decadal and multidecadal future warming trends if eruptions are clustered together, as found in some of the stochastic eruption scenarios. The post-eruption cooling also yields increased variability in global-mean surface temperature, highlighting the role of natural climate fluctuations in the quantification of climate projections uncertainty. Beyond post-eruption cooling, there is more richness in basically all aspects of climate variability, agreeing with the now countless indications from the scientific literature that volcanic radiative perturbations trigger dynamical adjustments and feedback loops that involve the whole earth system, from atmosphere and ocean to cryosphere and land. The less strong and less certain warming of the planet has obvious impacts on when climatic thresholds are reached in the simulations, including those assumed in socio-economic agreements. A well known sensible threshold is, for instance, an ice-free Arctic climate in September which a recent study based on observationally constrained climatic projections from CMIP6 suggests could occur within the next two decades (Kim et al., 2023). Accounting for stochastic eruption scenarios may revise such estimates significantly.

There is a discussion on how the volcano-climate connection should be represented in current climate simulations. The complete chain of propagating uncertainties was unexplored in the context of climate projections before CHIM23, and only rarely approached in other ambits of climate modeling. The paper is thus interesting from a methodological perspective, as its combined plume-aerosol-chemistry-climate model UKESM-VPLUME allows considering the whole complexity of the volcano-climate connection, from the source to the response and including climate-volcano feedbacks. However, this is just one model system, and how much such a comprehensive approach is viable and the results interpretable in a multi-model framework is not straightforward to determine. In fact, to understand differences across model results, ongoing coordinated international initiatives opted for breaking down the chain of uncertainty in the dominant processes linking volcanic eruptions and climatic response, most noticeably distinguishing the parts "from the source to the forcing" and "from the forcing to the climatic response" (Zanchettin et al., 2016). This is because increasing model complexity may increase the realism of the simulations but, given substantial uncertainties, it does not necessarily yield improved process understanding or inter-model agreement. For example, an experiment with a tight protocol built on characteristics of the 1815 Tambora eruption was performed with several chemistry-climate models to identify a consensus aerosol forcing data set for the volc-long-eq experiment of the CMIP6 initiative VolMIP (Zanchettin et al., 2016). The results showed large uncertainties in the estimated volcanic forcing parameters, which prevented the identification of a consensus data set and required a dedicated study to be understood (Clyne et al., 2021).

Despite a multi-model expansion of the work with UKESM-VPLUME seems far-fetched, studies like CHIM23 and, earlier, Aubry et al. (2019, 2021), have been inspiring new experiments for a possible next phase of VolMIP. Among these is volc-long-21C, an idealized experiment with the same Tambora-like equatorial eruption used in volc-long-eq but occurring under late-21st-century instead of preindustrial conditions. The experiment, defined for earth system models and using prescribed aerosol optical properties, requires careful consideration of the climate-volcano feedback in the light of inter-model differences not only in the amount of projected warming but in the preindustrial mean climate state (and model biases) as well. Results from the preindustrial Pinatubo-like VolMIP experiment volc-pinatubo-full indicate that minor differences in forcing implementation and model specificities regarding the tropopause height contribute to inter-model disagreement in the generated volcanic forcing (Zanchettin et al., 2022). A tighter coordination and mutual exchange between realistic and idealized approaches is thus the way to go for improved understanding of the linkages between volcanic eruptions, climate state, radiative forcing, and climate response.

Finally, beyond academic discussions, the question rises of how to communicate uncertainties and unknowns of the natural earth system and their impact on projected anthropogenic climate change. On the one hand, how researchers communicate about uncertainty can undermine trust and acceptance of scientific information about climate change (Ho & Budescu, 2019); on the other, there is also growing polarization of public discussions on climate in social media (Falkenberg et al., 2022), where antagonistic positions are often trenched to defend aprioristic convincement or belief about an absolute rather than uncertain (scientific) truth. The Intergovernmental Panel on Climate Change complains that there are "misperceptions of the scientific consensus, uncertainty, disregarded risk and urgency, and dissent" due to misinformation on climate change and deliberate undermining of science (Hicke et al., 2022). The volcanic forcing uncertainty described by CHIM23 appears to be intrinsically irreducible: while we can narrow down the range of possible climate futures by discriminating plausible from implausible social scenarios (Engels & Marotzke, 2023), volcanic scenarios are and will remain in this sense indiscernible. This fundamental uncertainty is very delicate to achieve a trustworthy, undistorted public perception. Volcanoes, with their relevance for past, present and future climates, and their unpredictability, may offer an opportunity to find a new paradigm for climate change communication.

Data Availability Statement

All data is available from public archives. The Berkeley Data set was retrieved from https://berkeleyearth.org/data/; Effective radiative forcing estimates were retrieved from https://github.com/IPCC-WG1/Chapter-7/blob/main/data_output/SSPs/.

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