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# Volcanic eruptions and climate: A complex interplay

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## ABSTRACT

Volcanic eruptions not only inject large quantities of gases and aerosols into the atmosphere but also impact global climate dynamics through complex interactions with atmospheric circulation and radiation balance. These eruptions can lead to short-term cooling due to the reflection of solar radiation by sulfate aerosols in the stratosphere, yet the long-term consequences and feedback mechanisms are still not fully understood. The challenge for climate models lies in accurately simulating these transient and regionally diverse effects, which are influenced by factors such as eruption size, latitude, and seasonality. Moreover, the underrepresentation of volcanic forcing in future climate projections underscores the need for improved modeling frameworks that can better account for the full range of volcanic impacts on climate variability. Integrating more comprehensive datasets and refined modeling techniques could enhance our ability to distinguish between natural volcanic influences and anthropogenic drivers like greenhouse gases and aerosols. This distinction is critical for robust climate projections and policy formulation aimed at mitigating future climate change impacts. The study by Man Mei Chim and colleagues sheds light on these complexities by exploring how volcanic activity may intensify under future warmer conditions, potentially amplifying climate. By addressing these uncertainties, the study underscores the importance of refining climate models to capture the nuanced interactions between volcanic forcing and global climate dynamics. This research not only highlights the repercussions of simplified climate scenarios but also advocates for continued investigation into the diverse impacts of volcanic activity on Earth's climate system.

## KEYWORDS

Volcano; Volcanic eruption; Aerosols; Climate

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## Introduction

Volcanic eruptions constitute a significant natural driver of Earth's climate: Following major explosive eruptions, Sulfate aerosols temporarily increase in the stratosphere, reducing the amount of solar radiation hitting the planet's surface and inducing an impact of global cooling. These are sporadic, random, potentially catastrophic, and unpredictable. Climate scientists face a daunting challenge when it comes to understanding the link between volcanoes and climate. Volcanic activity has long been considered a potential driver of weather and climate fluctuations. As far back as 2000 years ago, Plutarch and others noted that the eruption of Mount Etna in 44 B.C. darkened the Sun, leading to cooling that affected crop yields and contributed to famines in Rome and Egypt [1]. The eruption of Lakagigar in Iceland in 1783 is thought to have caused the unusually cold summer in Europe that year and the cold winter of 1783-1784 [2]. Humphreys linked cooling periods following major volcanic eruptions to the radiative impact of stratospheric aerosols, although at the time, there were limitations in the availability of long-term and widespread temperature data to quantify these effects [3]. Mitchell pioneered superposed epoch analysis by averaging the impacts of multiple eruptions to isolate the volcanic effect from other presumably random fluctuations [4]. Examining radiative forcing over historical periods already highlights the distinctive nature of volcanic eruptions among other forcing agents. The seemingly sporadic occurrences of volcanic adverse spikes of varying intensity contrast with the gradual development of other usual and human-caused forcings. The radiative impact of volcanic aerosols can be sufficiently potent that during major events, it temporarily surpasses the Earth's energy balance. Such as, the 1991 Pinatubo eruption's aerosols countered, at its height, the total net radiative forcing of all other agents during a time when manmade greenhouse gas emissions would have otherwise had an impact. After Pinatubo, global tropospheric temperatures dropped by as much as 4°C, although winters in the northern hemisphere experienced warming.

Volcanic eruptions release tens of teragrams of chemically and microphysically active gases and solid aerosol particles into the stratosphere. These substances influence the Earth’s radiative balance, impact climate, and disrupt the chemical equilibrium of the stratosphere. The volcanic cloud forms over several weeks as sulfur dioxide (SO2) converts to sulfate aerosols and undergoes subsequent microphysical transformations [5,6]. The sulfate aerosol cloud that forms, with an e-folding decay time of around 1 year, significantly influences both shortwave and longwave radiation [7]. This disturbance to Earth's radiation balance impacts surface temperatures directly through radiative effects and indirectly through effects on atmospheric circulation. In cold regions of the stratosphere, these aerosol particles also act as surfaces where heterogeneous chemical reactions occur, releasing chlorine that contributes to ozone destruction, similar to how water and nitric acid aerosols in polar stratospheric clouds lead to the formation of the seasonal Antarctic ozone hole.

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## Volcanic Inputs to the Atmosphere

Volcanic emissions discharge different sorts of particles and gases into the air. Prior estimates of these emissions primarily relied on data from ongoing eruptions, often excluding explosive events, and on remote sensing technologies such as lidar, radiometers, and satellites to observe resulting aerosol clouds. However, the accidental discovery of the Total Ozone Mapping Spectrometer (TOMS) instrument's ability to detect sulfur dioxide ($SO_2$) has introduced a novel approach for directly measuring the injection of gases into the stratosphere during volcanic eruptions [8].

Major volcanic eruptions have a pronounced effect on Earth's climate by dropping the quantity of solar radiation reaching the surface, which brings down the temperatures in the lower troposphere and triggers changes in atmospheric flow forms [9]. In contrast, sustained increases in carbon dioxide levels lead to warming effects on global temperatures [10]. Large-scale volcanic eruptions that eject ash into the stratosphere exert the most substantial climatic influences: the intensity and duration of the eruption directly determine the scale of its impact on climate dynamics worldwide [11].

These kinds of emissions are remembered to play had an impact in starting the Little Ice Age, a worldwide cooling stage that endured from the fifteenth to the late nineteenth 100 years, resulting in a temperature drop of approximately 0.5°C [12]. Super volcanoes like Yellowstone (USA), Toba (Indonesia), and Taupo (New Zealand) possess the potential to produce immensely large-volume eruptions that can significantly impact climate conditions. However, uncertainties persist regarding the duration and extent of their climatic effects on a global scale [13].

## Volcanic vs Anthropogenic Emissions

Arguably, the most compelling evidence to assess the relative impact of human emissions versus volcanic movement on the environment lies in the size of ozone-harming substance emissions. Starting around 2015, yearly worldwide anthropogenic carbon dioxide outflows have varied between 35 to 37 billion tonnes, driven principally by human exercises like petroleum product ignition and deforestation [13]. In contrast, volcanic emissions of $CO_2$, averaging around 200 million tonnes annually, represent a significantly smaller contribution to the overall carbon budget of the atmosphere [14]. This stark contrast underscores the dominant role of human-induced emissions in driving contemporary climate change compared to volcanic sources. In 2018, human-caused $CO_2$ emissions surpassed volcanic emissions by a factor of 185 [9]. This significant disparity underscores the profound impact of human activities on Earth's carbon budget and climate system. This statistic has led geologists and normal researchers to advocate for perceiving another land age known as the Anthropocene. The Anthropocene concept acknowledges that human activities, particularly since the mid-20th century, have exceeded the influence of many natural global processes, fundamentally altering Earth's environment and ecosystems [15].

There is ample evidence that volcanoes have exerted a notable influence on climate over extended geological epochs [16]. Nonetheless, since 1950, human activities, particularly those involving Homo sapiens, have overwhelmingly been the dominant force shaping global climate patterns [17]. It is imperative that we persist in our efforts to curb $CO_2$ emissions without banking on the possibility that volcanic activity will offset the consequences of anthropogenic climate change [9]. Carbon dioxide ($CO_2$) is a greenhouse gas and plays a pivotal role in driving climate change [9]. Recent volcanic eruptions have occasionally released sulfur dioxide, which can induce temporary global cooling by reflecting sunlight in the lower atmosphere [18]. However, the C02 produced during these ejections has not been linked to detectable global warming effects [14].

In contrast, human activities have significantly intensified $CO_2$ emissions. In 2010 alone, human activities released approximately 35 billion metric tons (gigatons) of $CO_2$ into the atmosphere [13]. This dwarfs the combined emissions from contemporary volcanic sources—both subaerial and submarine—which account for less than one percent of current human $CO_2$ emissions [19]. There is ongoing scientific debate about the potential role of intense volcanic $CO_2$ emissions in ancient times. Some hypothesize that these emissions contributed to global warming and may have even played a part in mass extinctions [20]. However, conclusive evidence remains elusive, and researchers continue to study these phenomena to understand their full impact on Earth's climate history [21]. The disparity between volcanic and human-induced $CO_2$ emissions underscores the dominant role of anthropogenic activities in current climate change trends. It emphasizes the importance of reducing human $CO_2$ emissions to mitigate future climate impacts and underscores the complexity of natural versus human-induced climate drivers in Earth's history and future projections [10].

## Climate Impacts of Large Eruptions

Large volcanic eruptions have significant impacts on global climate for several reasons. Firstly, these eruptions release substantial amounts of carbon dioxide gas which is a greenhouse gas known for contributing to the greenhouse effect by tricking heat emitted from the surface of the Earth, thereby maintaining a habitable temperature range [22]. However, concerns are growing that human activities, particularly the combustion of fossil fuels, are pushing this natural balance beyond its limits, resulting in accelerated global warming [10].

Although volcanic eruptions emit $CO_2$, their contribution is relatively minor compared to human activities. On average, volcanic ejections discharge around 110 million tons of $CO_2$ yearly [23]. In stark contrast, human activities release nearly 10,000 times that amount each year [10]. This vast disparity highlights the overwhelming impact of anthropogenic $CO_2$ emissions on the Earth's climate system [17].

Understanding these distinctions is crucial for developing effective strategies to mitigate climate change. While volcanic eruptions play a role in natural climate variability, human-induced emissions remain the primary driver of contemporary global warming trends [10]. Efforts to reduce and stabilize human $CO_2$ emissions are essential to limit future climate impacts and safeguard planetary health [10].

## Global Dispersion of Volcanic Aerosols

The ash and aerosol clouds resulting from major volcanic eruptions disperse swiftly throughout the atmosphere. One of the most notable examples occurred on August 26 and 27, 1883,

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when the Krakatau volcano exploded catastrophically, ejecting approximately 20 cubic kilometers of material into an eruption column nearly 40 kilometers high [24]. The immediate aftermath saw darkness enveloping the nearby Indonesian islands of Java and Sumatra. However, fine particles were quickly conveyed by climatic flows toward the west. By the afternoon of August 28th, fog from the Krakatau emission had previously reached similar to South Africa. By September 9th, the haze had circled the globe, completing several circuits before gradually settling out of the atmosphere [25]. This widespread dispersion of volcanic aerosols illustrates how major eruptions can have a global reach, impacting atmospheric conditions across vast distances and highlighting their significant role in Earth's climate system [13].

## Artistic and Cultural Influence

Main volcanic emissions produce climatic impacts that reach out past simple worldwide temperature decreases and corrosive downpour. Debris and spray particles suspended in the air dissipate red-frequency light, frequently resulting in spectacularly colorful sunsets and sunrises visible worldwide [13]. The remarkable optical displays produced by the Krakatau eruption cloud in 1883 were observed globally and likely influenced many artists and authors in their creative endeavors. For instance, the radiant and vivid portrayals of the fiery evening sky over the Thames River in London by British painter William Ascroft may have been inspired by the distant and awe-inspiring Krakatau eruption [25]. Such artistic interpretations not only reflect the profound impact of volcanic phenomena on human culture but also underscore the enduring fascination with the natural world's dramatic displays.

## Long-term Climate Variations

Geological evidence indicates that natural processes possess the capacity to exert substantial changes on Earth's climate. Over the past 100 million years, there have been notable shifts such as cooling of ocean bottom waters, reductions in sea levels, and expansions of ice sheets [26]. Within this timeframe, there have also been intervals of warmer global conditions, often attributed to rapid natural releases of greenhouse gases [27]. These natural climate fluctuations underscore the dynamic and interconnected processes shaping Earth's long-term climate history [10].

## Human Evolution and Climate

Homo sapiens evolved over the course of several million years, predominantly during a period known as the ice age. This epoch was marked by vast ice sheets, reaching thicknesses of up to two kilometers, that covered significant portions of the northern continents [28]. Sea levels during this time were more than 100 meters lower than they are today [29]. Approximately 10,000 years ago, this ice age epoch gave way to our current interglacial period, characterized by a warmer climate and a reduction in ice coverage. This transition marked a pivotal moment in human history, as early societies adapted to the changing environmental conditions and the opportunities presented by a more hospitable climate [30].

## Astronomical and Geological Factors

Cosmic cycles liable for environment varieties are surely known, for example, the Milankovitch cycles, which represent switches in Earth's circle up the sun, and the occasional shifting and precession of Earth's pivot [31]. However, the tectonic and geological factors contributing to the overall long-term cooling of Earth are less clear. Hypotheses include influences from volcanic activity and processes associated with the formation of the Himalayas and Tibet, dating back approximately 55 million years ago [32].

## Conclusions

The science of volcanic effects on climate has advanced significantly over the past two decades, driven by improved observational capabilities, improved proxy records of temperature changes, and sophisticated ice core reconstructions. Aerosol-climate models offer valuable insights into the uncertainties associated with volcanic eruptions thanks to their state-of-the-art capabilities. Initial estimates suggest that volcanic plumes have limited potential to cool the globe as a result of their modest $SO_2$ emissions, but ongoing studies are expected to improve our understanding of these processes and their impacts on regional weather. The development of better understanding of volcanic-climate interactions will require collaboration across disciplines, including atmospheric science, climate modeling, volcanology, and history.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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