Journal of
CATASTROPHE RISK
AND RESILIENCE

Journal of CATASTROPHE RISK AND RESILIENCE

Assessing Volcanic Hazards and Financial Exposure: A Closer Look at Insurance Industry Preparedness

Authors

James Dalziel
Willis Research Network
Willis Group Limited, 51 Lime Street, London, EC3M 7DQ, United Kingdom
ORCID: https://orcid.org/0000-0002-0341-3260
Email: james.dalziel@wtwco.com

Michael Cassidy
School of Geography, Earth and Environmental Science, University of Birmingham
Edgbaston, Birmingham, B15 2TT, United Kingdom
Email: m.cassidy.1@bham.ac.uk

Lara Mani
Centre for the Study of Existential Risk, University of Cambridge
16 Mill Lane, Cambridge, CB2 1SB, United Kingdom
ORCID: https://orcid.org/0000-0003-2967-7499
Email: lm881@cam.ac.uk

Acknowledgements
This work was undertaken as part of an unfunded research partnership between the Willis Research Network and the Global Volcano Risk Alliance, a registered charity dedicated to mitigating the risk from globally impactful eruptions through preparedness, monitoring, and advocacy for anticipatory action.

Journal of CATASTROPHE RISK AND RESILIENCE

Abstract

Within the insurance and reinsurance sectors, volcanoes and their secondary impacts are often an overlooked risk due to the long return periods associated with large explosive eruptions, and relatively low economic and insured losses from eruption events compared to other natural hazards such as large magnitude earthquakes. However, with continued population growth, globalisation and climate change increasing exposure to volcanoes, and more sophisticated monitoring and modelling methods revealing the true extent of both primary volcanic hazards and secondary effects, this is a peril that should be more thoroughly considered. This study reviews exposure to active Holocene volcanoes, compares economic and insured losses of significant eruptions, and explores how analogues of historic events could affect the modern world. We show that the past 40 years have mostly seen eruptions of Volcanic Explosivity Index (VEI) 3–4; significant but not “super-catastrophes.” Should a larger VEI 6+ event occur near a densely populated area or in a country with high insurance penetration, losses could be far higher. Countries with the highest exposed populations to volcanoes include Indonesia, the Philippines and Guatemala. However, this differs from countries at greatest risk of insurable losses, such as China, Japan and the US, and lower insurance penetration in more exposed countries identifies a significant protection gap. Eruptions in smaller nations show particular financial vulnerability, with recent eruptions in Tonga and La Palma leading to large losses in proportion to their GDP; as much as 1/3 of their economy (30-37%). The economic losses of accumulated volcanic activity have totalled $152.6 billion over 20 years (an average of $7.6 billion a year). Recent estimates that a large, long return period, global climate-affecting eruption might lead to losses in the multi-trillions, and would impact pre-existing reinsurance markets in a similar manner to tropical cyclones, highlights the need for greater attention, preparedness and resilience measures. With this in mind, we discuss current research and industry initiatives to collate volcanic data, to aid disaster risk reduction strategies. It is hoped that by working with such organisations, and helping facilitate global standardisation of data and risk communication, the insurance industry can be better prepared for future volcanic eruption scenarios.

Keywords: Volcanic hazard; Risk; Exposure; Insurance; Preparedness

Introduction

Within the insurance and reinsurance sector, volcanic risks are not usually at the forefront of many broking conversations. In the eyes of the insurance industry large-scale eruptions are less frequent and either less damaging than large magnitude earthquakes, or in the case of the most extreme eruptions so damaging they are considered uninsurable. By comparison, earthquakes occur regularly all over the world with very little warning, and when large magnitude events coincide with urban areas and sub-standard building practices the results can be devastating and costly. The Türkiye-Syria earthquake became 2023's most destructive and costliest natural disaster, totalling overall losses of US$50bn and insured losses of US$6.2bn (Perils AG, 2024). There are still a number of large urban centres built around active volcanic centres, including Bandung, Manila, Auckland, Naples, Mexico City, Tokyo and others (see Figure 1), and the range of hazards resulting from an eruption can vary between volcanoes as well as between phases of a single eruption event with potential for significant losses. Eruptions in highly exposed locations (Figure 1) do not necessarily need to be large, i.e. Volcano Explosivity Index (VEI)-6+, in order to have a high impact on urban environments not used to such hazards. Such events are referred to in the insurance industry as 'fat-tailed' or 'global catastrophic' risks; those with lower probabilities and therefore repeat times, but capable of resulting in significant losses with the potential to affect multiple countries beyond that of its origin (Blong, 2021).

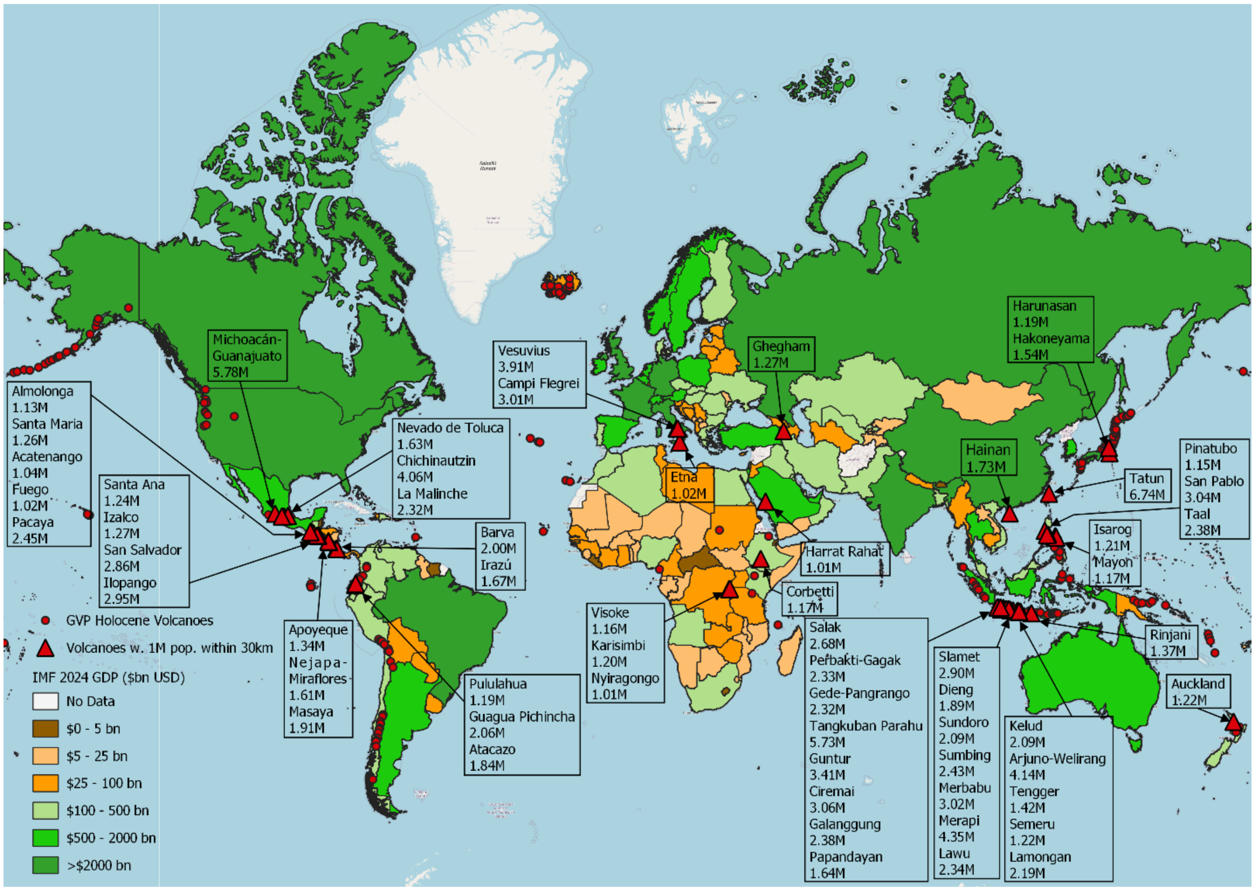


Figure 1: *Global distribution of Holocene volcanoes (red dots), with populations of >1 million within a 30 km radius (red triangles). Source: Smithsonian Global Volcanism Program. This includes Indonesia (n=21), Philippines, Guatemala (n=5), Mexico, El Salvador (n=4), Nicaragua, Ecuador, Italy (n=3), Japan, Rwanda, Costa Rica (n=2), Taiwan, China, Armenia, Saudi Arabia, Ethiopia, DR Congo & New Zealand (n=1). Countries coloured according to 2024 GDP. Source: International Monetary Fund.*

There have been some attempts to develop volcanic loss models for insurers, including a probabilistic volcanic loss model for New Zealand based on tephra fall thickness (Magill et al., 2006), and a parametric risk transfer mechanism based on eruptive column height and ash dispersal direction (Oramas-Dorta et al., 2021). Despite this, these models tend to have been abandoned or not widely adopted by the wider industry due to low return periods of high-impact eruptions, the wide range of possible volcanic hazards that could result, and uncertainties associated with if, when and where these hazards will appear. However, these limitations have the potential to leave insurers unprepared if a high impact eruption were to occur. Therefore, priority should be made to develop robust probabilistic models for an array of volcanic hazards and eruptions scenarios to better understand potential insurable losses for the insurance sector, and to help reduce the impacts during future eruptions.

This paper aims to briefly identify the volcanoes that present significant risk, both in terms of human and financial exposure, the range of eruption products and secondary hazards associated with volcanic activity, possible losses arising from these based on historical events and analogue settings, and suggestions of how ongoing research to improve monitoring, modelling and forecasting may be able to better quantify these risks in order to aid better resilience, emergency planning and policymaking.

Exposure to volcanic risks

Figure 1 shows a comparison of country GDP against Holocene volcanoes with large populations nearby (within ~30km), and reveals that the majority of this high risk exposed locations are concentrated in south-east Asia (mostly Indonesia) and Central America. With the notable exceptions of Italy and Japan, there are significantly fewer volcanoes with large populations nearby in high GDP economies.

Figure 2 provides an insight about which countries are more at risk than others from an insurance perspective, by comparing the number of active Holocene volcanoes (those which have erupted within the last 10,000 years) with the total insurance penetration values per country. Insurance penetration is used as an indicator of insurance sector development within a country, and is calculated as the ratio between total value of insurance premiums against Gross Domestic Product (GDP) in a given year (OECD, 2024). This can be the value for total insurance premiums, or divided into categories such as life versus non-life (e.g. contents) insurance. Another metric for measuring insurance within a given country is the take-up rate, which compares the number of people or organisations taking out insurance premiums against the total number eligible.

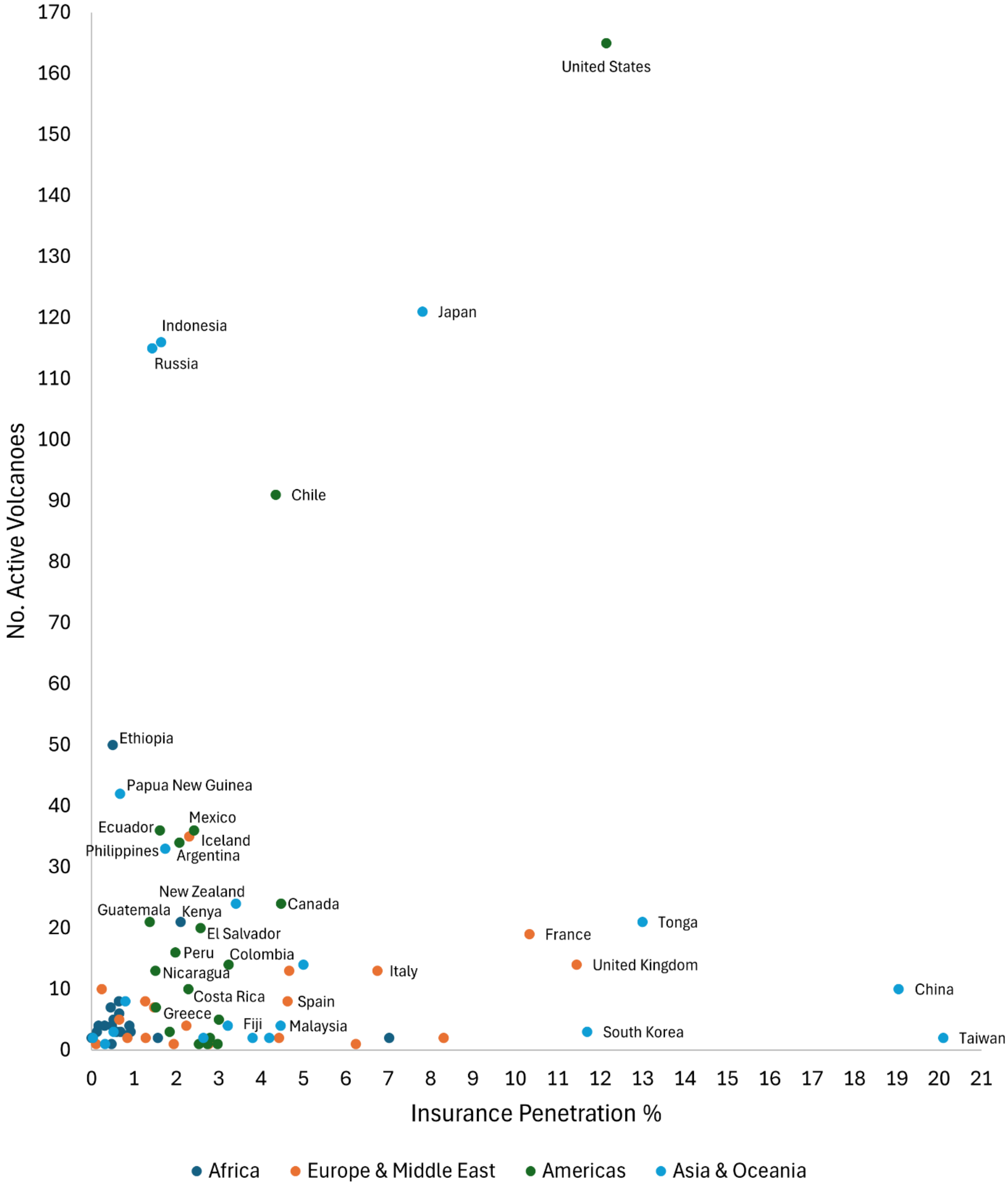


Figure 2: *Insurance penetration vs. number of Holocene volcanoes by country. Insurance penetration measures total value of premiums as a percentage of GDP in a given year. Includes overseas territories,*

e.g. UK and France. Source: Volcano data from Smithsonian Global Volcanism Program, insurance data from OECD, Africa Re & Axco.

At a glance, this would suggest that countries like China and Taiwan are at relatively lower risk (showing high penetration and a lower number of volcanoes), while countries like Japan, Chile, Indonesia, Russia and the US will be more at risk of higher insured losses. Countries with a moderate number of active volcanoes and very low penetration, such as Ethiopia and Papua New Guinea, are likely to not be covered by a potential volcanic disaster.

Examining the data more closely shows that although some countries may have fewer volcanoes, some urban areas are particularly exposed (e.g. Taipei in Taiwan, or Naples in Italy). Some of these are also showing increased unrest, for instance the Campi Flegrei volcano, Italy (e.g. Kilburn et al., 2023). Measurement of crustal stresses, gas ratios and long-term deformation at the volcano suggests there may be an increased risk of eruption (Ferrara et al., 2025), and given the proximity to Naples this is a risk that should be considered in relation to business interruption, tourism and air travel to name a few (Kilburn et al., 2023, Caliro et al., 2025). A past study from the Willis Research Network and its partners suggested even a moderately-sized eruption of nearby Mount Vesuvius could result in economic losses of $24 billion USD (Spence et al., 2010), or $34.6 billion USD adjusted for inflation, with insured losses likely comprising a proportion of this despite relatively low insurance take-up. According to Lloyd's 'Future Set' tool, an eruption scenario similar to the 2010 Eyjafjallajökull eruption with an ash cloud that covers the local area to 5cm depth would generate $74 billion USD economic losses over 1 year, growing to $91 billion USD over 5 years (Lloyds & CCRS, 2024). Although not recently affected by volcanic unrest or activity, following the 2011 Mw9.0 Tohoku earthquake and a subsequent Mw5.9 aftershock beneath the south flank of Mt. Fuji, close to its magma system, questions were asked whether stress field changes could trigger an eruption like that in 1707. A similar eruption would affect major urban centres such as Tokyo (Fujita et al., 2013), generating significant losses.

Worldwide there are over 1 billion people living within 100 km of an active volcano, more than 14.3% of the global population (Freire et al., 2019). Many additional volcanoes will have exposed populations in the millions or even tens of millions over the next few years, given the increasing population trend. Freire et al. (2019) also notes that human concentrations in this 100 km zone have been increasing since 1975, above the global population growth rate. In south-east Asia, the highest population growth rates have occurred within 10 km of volcanoes, with the region being home to over 12% of Holocene volcanoes and 15% of Holocene eruptions according to the Global Volcanism Program (Jenkins et al., 2022). Indonesia and the Philippines are estimated to contain more than 75% of global volcanic threat, calculated from average Volcanic Hazard Index, number of volcanoes and population within 30 km of volcanoes (Brown et al., 2015b). Jenkins et al. (2024) found that across Africa there is potential for eruptions to distribute tephra across large cities, key infrastructure such as geothermal power stations, tourist destinations, seats of government and emergency management operations in close proximity to active volcanoes.

There are similar considerations for other volcanically active areas such as New Zealand, Indonesia, Hawaii, Iceland or the Western US, with the added complication that these areas will have a variety of potential volcanic hazards depending on their location, geology and eruptive history. Volcanoes that tend to have explosive eruptions can cause widespread damage and disruption through fast-moving pyroclastic flows (e.g. Mount St Helens, 1980), lahars (e.g. Nevado Del Ruiz, 1985) and ash clouds (e.g. Eyjafjallajökull, 2010), whereas effusive eruptions such as those across Hawaii and in south-western Iceland present smaller-scale hazards such as lava flows and sulfur dioxide release that will still affect nearby assets but are less likely to have as widespread of an impact. An article by climate risk intelligence company Mitiga Solutions (Strehlow, 2023) explains the range and potential impacts of these volcanic hazards, and a paper by Mani et al. (2021) identifies seven global 'pinch-points' where the convergence of critical infrastructure (such as air traffic, shipping routes and submarine communications cables) mean that even a moderately-sized eruption could incur significant losses.

Relative financial losses from volcanoes

We know that the hazards from volcanoes can be variable and wide-reaching, and exposure to these hazards can be significant in some parts of the world. Viewed through the lens of a catastrophe insurance market point of view, the key is comparing insurable losses in a calendar year from currently modelled natural hazards such as windstorm, earthquake & flood events against volcanic eruption events. Have any of these volcanic events been insurance market defining? These events are clearly devastating to the countries involved, but how much do they impact the loss ratios of the insurance market and how much could they in a worst-case scenario?

For the insurance and reinsurance industries, large and catastrophic events with high losses tend to act as a catalyst for change, and increase in demand for capacity to model and suitably cover similar disasters in future. For example, Hurricane Andrew in 1992 caused approximately $27 billion in damages (over $50 billion today), leading to the insolvency of several insurance companies that were unprepared for such massive losses. This highlighted the need for better risk management and more substantial financial backing to model such large weather events, as insurers realized their exposure to these was greater than previously estimated. Following this, there was a significant increase in demand for reinsurance as primary insurers sought to protect themselves against similar future events, and increasingly now in the face of anthropogenic climate change, resulting in growth for the reinsurance market as more companies entered the space and existing reinsurers expanded their capacity. It could be argued that there have been fewer similarly large precedents set for volcanic catastrophes, meaning that the insurance industry is unprepared for the form and extent of losses from such events.

The United Nations assessed the economic damage caused by all types of natural disasters between 1995 and 2015, and found that geophysical disasters (volcanoes and earthquakes) costed $763 billion during that period (Breene, 2016) (Figure 3). Of these disasters, 20% were volcanic, putting the cost of volcanic activity at $152.6 billion over 20 years (or an average of $7.6 billion a year).

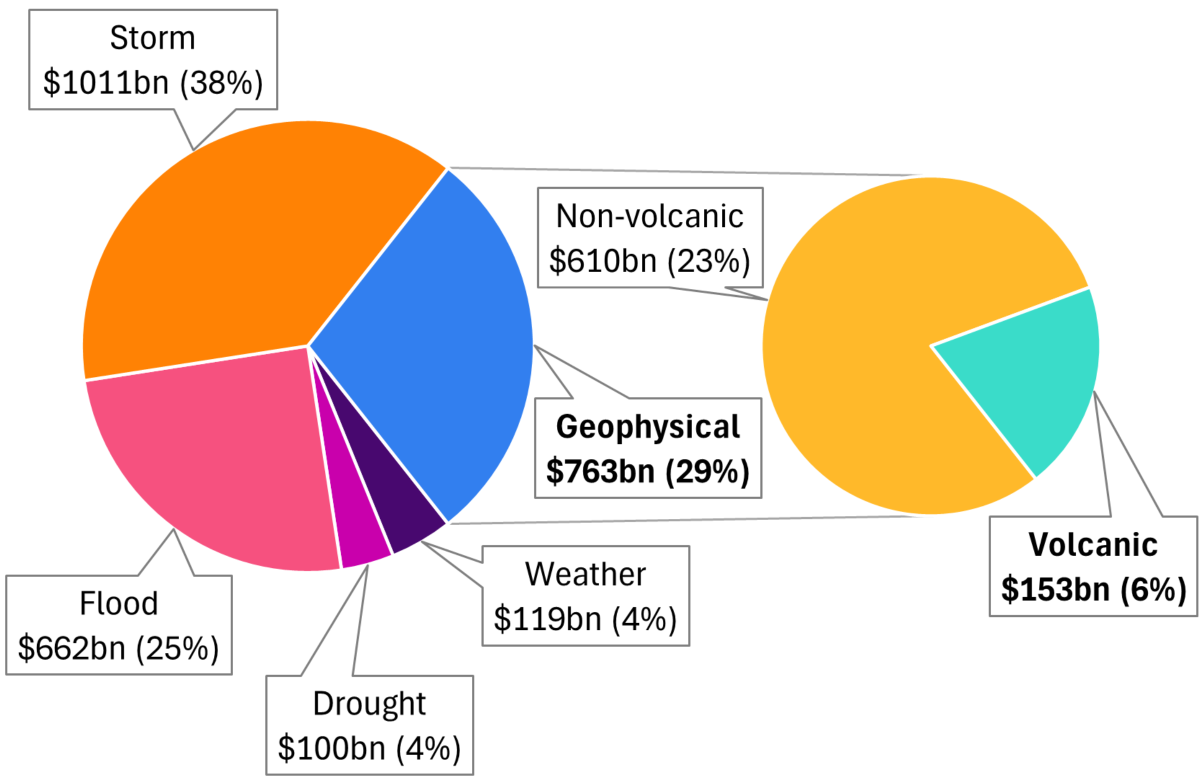
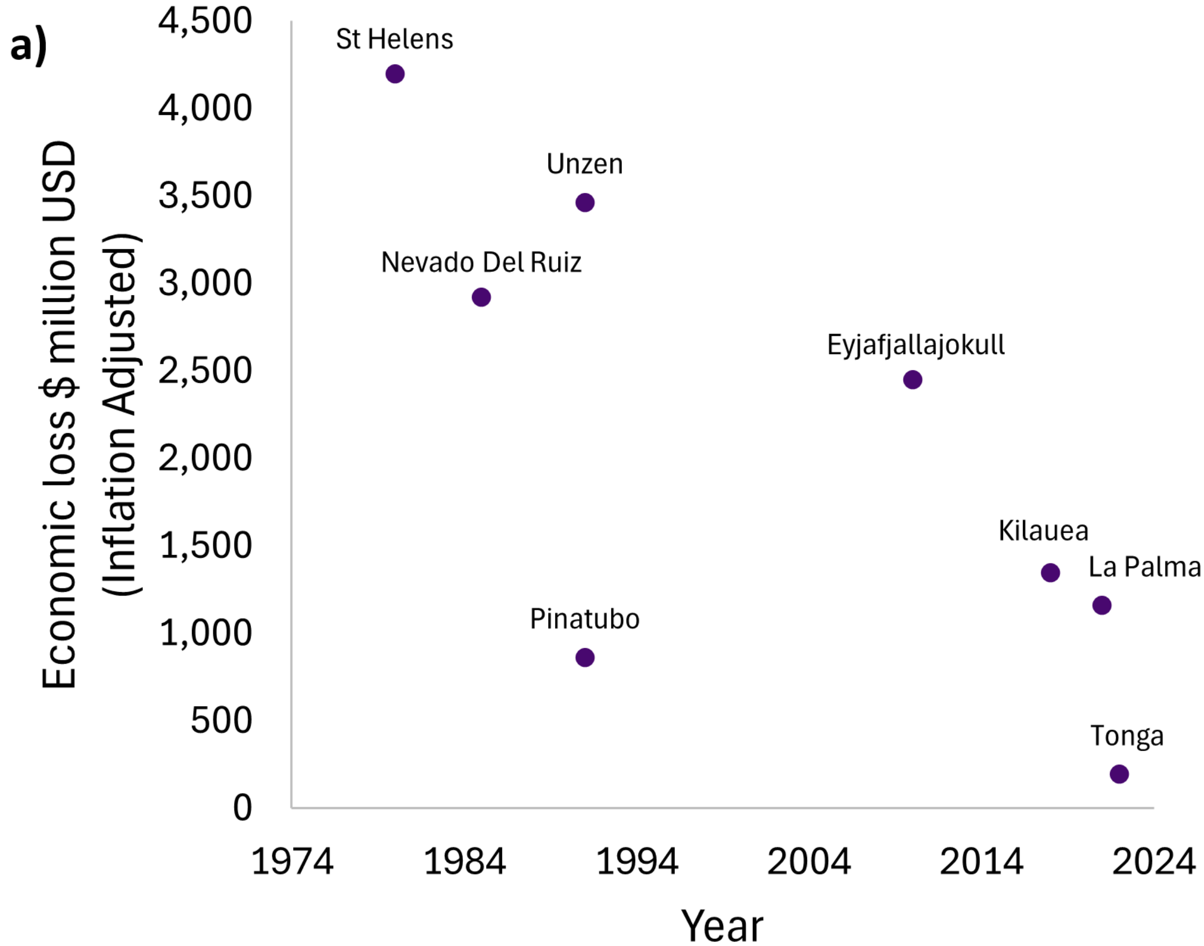


Figure 3: *Economic damage by natural disaster type, 1995-2015. Source: United Nations International Strategy for Disaster Reduction.*

According to Verisk's 2024 Global Modelled Catastrophic Losses Report, insured Annual Average Loss (AAL) from natural catastrophes have increased from $74.4 billion in 2015 (when the UN's study period for economic losses ends) to $151.1 billion in 2024 (Verisk, 2024). Although volcanic perils aren't included in these statistics, 'Earthquake' is shown to contribute 10% of this value.

Like the range of hazards described, volcanic eruptions can also cause different types of loss. These comprise of direct losses, e.g. fatalities, destruction and damage to buildings and infrastructure, and indirect losses, e.g. loss of livelihoods, contaminated drinking water supplies and crops, disruption to business and tourism via disrupted air travel, and long-term environmental impacts (Lockwood & Hazlett, 2010). Volcanic ash fall, when combined with rain, can also cause flashover of electrical lines leading to widespread outages and disruption of power grids (Wilson et al., 2012, 2015). This leads to further knock-on effects, business interruption and indirect losses (Mani et al., 2021).

Values can vary between sources, but statistics from Munich Re give the greatest overall economic loss from an individual volcanic eruption as Mount Unzen, Japan (1990-1995) at $1.5 billion ($3.5 billion adjusted for inflation) with an insured loss of $130 million (or $300 million today), and the greatest insured loss as the 2021 La Palma eruption at $260 million (with an economic loss of $1 billion) (Käser & Rauch, 2022) (Figure 4 a). Other significant losses from volcanic eruption include the 1980 Mount St Helens eruption; although quoted by Munich Re as having $860 million in economic losses and $30 million insured losses, a Washington Post article written in the months after the event quoted government figures of over $1.1 billion ($4.2 billion adjusted for inflation) in damage to property, rivers, roads, bridges, and the timber, agriculture and fishery industries in Washington and Oregon (Seaberry, 1980) (Figure 4a). Smart's Insurance Bulletin, May 18, 1981, reported over 40,000 insurance claims were filed, 166 recovery loans were applied for and $215 million ($744 million adjusted for inflation) was spent on dredging rivers that year (Rees et al., 2012). According to figures provided by the International Disaster Database EM-DAT, the 1985 Nevado Del Ruiz eruption in Columbia also had a total economic loss of $1 billion ($2.9 billion adjusted for inflation), in addition to over 21,800 deaths caused by the resulting lahar and compounded by a severe storm impacting evacuation attempts (Breene, 2016, EM-DAT, 2023) (Figure 4a). And the International Air Transport Association stated that the total economic loss for the airline industry from the 2010 Eyjafjallajökull eruption was around $1.7 billion ($2.5 billion adjusted for inflation) (IATA, 2010) (Figure 4a). To make matters worse, many of the affected airlines weren't insured against loss of revenue caused by volcanic disruption, resulting in having to cover losses themselves (Blau, 2010). These eruptions are also highlighted in available EM-DAT data for economic losses by year, with the total loss value divided by the number of eruptions to give an average loss per eruption (Figure 4b).


a)
Economic loss $ million USD (Inflation Adjusted)
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
St Helens
Unzen
Nevado Del Ruiz
Eyjafjallajokull
Kilauea
La Palma
Pinatubo
Tonga
1974
1984
1994
2004
2014
2024
Year

256

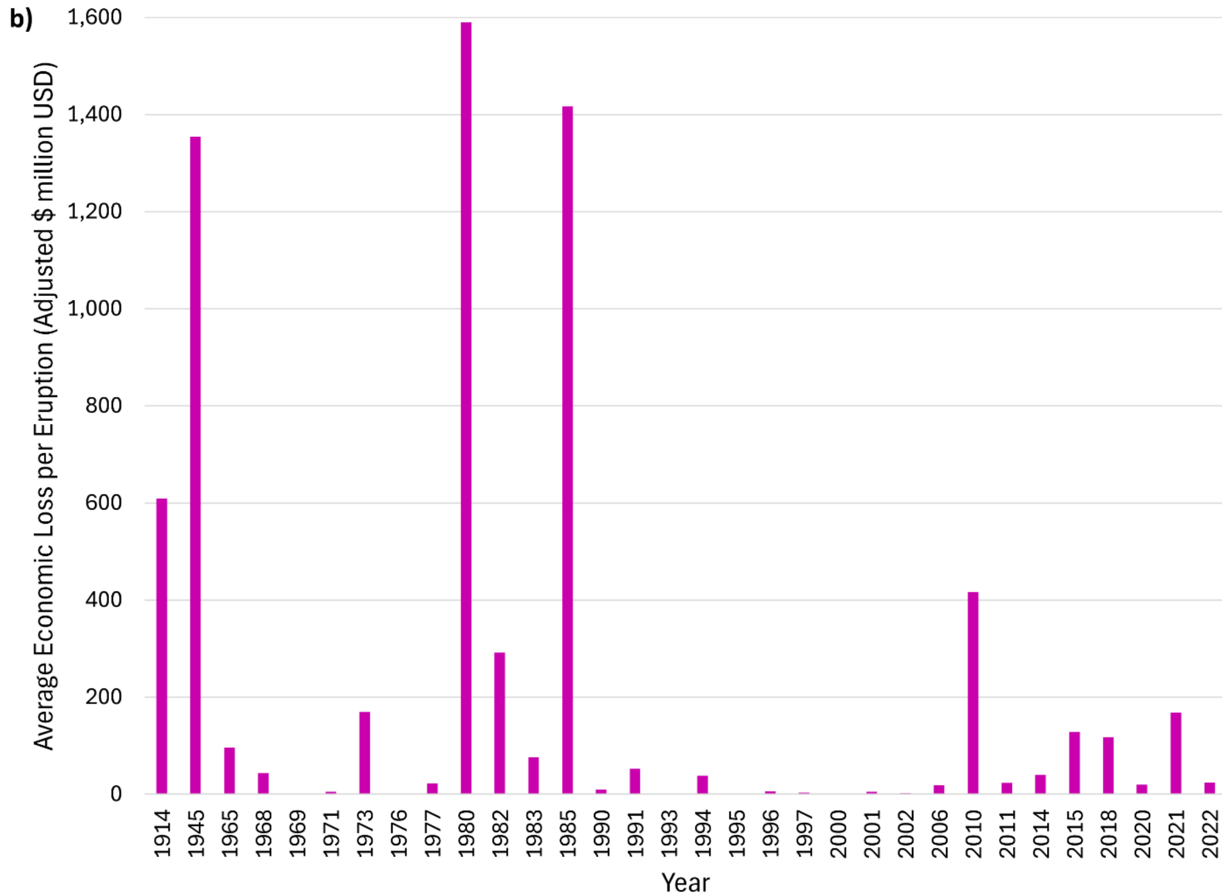


Figure 4: ***a)*** *Inflation-adjusted economic losses from volcanic eruptions in the past 50 years: St. Helens 1980, $4.2b (Seaberry, 1980), Nevado Del Ruiz 1985, $2.9b (EM-DAT, 2023), Pinatubo 1991, $0.9b (De Guzman, 2005), Unzen 1990-1995, $3.5b (Käser & Rauch, 2022), Eyjafjallajökull 2010, $2.5b (IATA, 2010), Kilauea 2018, $1.3b (Hawai'i County, 2019), La Palma 2021, $1.2b (Käser & Rauch, 2022) & Tonga 2022, $0.2b (Waradi & Perry, 2022).* ***b)*** *Economic loss divided by number of eruptions in a given year, adjusted for inflation. Source: EM-DAT, 2024.*

In comparison to these losses, the 2023 Turkey-Syria earthquake had economic losses of over $20 billion and insured losses of over $1 billion (Verisk, 2023). However, this equated to ~1% of Turkey's GDP, whereas the GDP impact of the 2021 La Palma eruption was over 30% (Rubert, 2021). The 2022 Hunga Tonga–Hunga Ha'apai eruption, considered to be one of the most powerful eruptions of the 21st century with significant ash release, triggered submarine landslides and tsunami causing damage to subsea communication cables as well as roads and vital infrastructure, cost $182 million in economic damage ($196 million today) (Waradi & Perry, 2022) with submarine cables repairs costing an additional $1 million to repair (ZMS Cable, 2022). This is equivalent to 36.4% of the country's GDP, and losses would be significantly higher if the volcano was not in such a remote area.

Looking to the past; analogues from historic large-magnitude eruptions

To get a better idea of the potential losses from larger, 'worst-case' event scenarios in more populated regions, there are a number of historic eruptions that can be examined in more detail. Although the economic losses for these events were not as accurately recorded as events in the last century, the resulting hazards and their effects on populations, livestock and regional weather patterns are well-documented enough to be projected for if they were to happen today.

The 1707 Mount Fuji eruption released ~0.68 cubic kilometres of ash which reached as far as Tokyo, and if a similarly sized VEI-5 eruption with an estimated recurrence rate of 50-60 years (based on eruption frequency data from the Smithsonian Institution Global Volcanism Program) (Venzke 2024) were to occur today it's estimated that between 0.5-16cm of ash would fall over the city (Cabinet Office of Japan, 2002). As well as airborne ash causing significant disruption to air traffic, such thickness of ashfall would cause damage to electricity transmission lines, transport networks, machinery, contaminate water sources and potentially result in structural damage to buildings (Wilson et al., 2012). Such an eruption would cause an estimated $22 billion in losses ($38.4 billion adjusted for inflation), not including infrastructure like transportation and power transmission (Cabinet Office of Japan, 2002).

The 1783-1784 Laki eruption was dominantly effusive, releasing large quantities of volcanic gases like sulphur dioxide (100 Tg) and fluorine over a number of months (Thordarson & Self, 2003). It caused up to 3 degrees of cooling in the Northern Hemisphere (Zambri et al., 2009). These gases combined with water vapour to create an acidic fog which spread across western Europe and Scandinavia, damaging plants, vegetation and crops, and depositing fluoride across Iceland which killed more than 60% of livestock from contaminated feed by the following year (Thordarson & Self, 2003). A sulfur-rich effusive VEI-4 eruption today with similar volcanic gas hazards would likely also cause widespread crop failures, livestock deaths and human respiratory issues. It is estimated that atmospheric contamination would cause an additional 142,000 deaths from cardiopulmonary issues across Europe (Schmidt et al., 2012), and with agriculture worth ~$375 million in revenue across Iceland alone in 2021 (Statistics Iceland, 2023) global economic losses would likely total billions. Although the UK Government's 2023 National Risk Register acknowledges the risks to aviation from volcanic eruptions, with a 'high impact, low probability' VEI-7+ eruption having the potential to cause major disruption to supply chains, international displacement, and hazardous weather, risks to human health, energy as well as financial security, agriculture and livestock are not discussed (HM Government, 2023).

One of the largest recorded eruptions in history was that of Tambora in 1815, however due to limited detailed records the monetary losses are difficult to quantify. Pyroclastic flows overwhelmed surrounding islands and caused tsunami waves as high as 4m, the release of ~60 million tonnes (60Tg) of sulphur dioxide (SO2) caused annual cooling over the next 3 years in the Tropics and Northern Hemisphere by ~0.4–0.8°C per year, relative to the previous 30 years (Raible et al., 2016) due to blocking incoming solar radiation, and estimated deaths across Indonesia were thought to range between 70,000-100,000 (Oppenheimer, 2003). Similar to a Laki-like eruption, the SO2 release and subsequent cooling from a Tambora-like event would likely result in crop failures and famines across multiple countries, as well as reduced global average precipitation leading to droughts, and increased likelihood or extreme climate events such as flooding and slope failures (Oppenheimer, 2011, Freychet et al., 2023). Estimates suggest the aftermath of such an event could disrupt food supply to between 1 – 2.9 billion people (Puma et al., 2015). To try and quantify costs of such an event, comparison of magnitudes from more modern eruptions can provide some clue.

Extrapolating from Mahalingam et al.'s 2018 economic study, which investigated the economic impacts of VEI-6 eruptions in Indonesia and US and estimated losses between $2.5-7.6 trillion USD, Cassidy & Mani (2022) suppose a VEI-7 eruption with its potentially larger climatic effects on food, water and energy security would exceed $10 trillion, comparable in magnitude as the COVID-19 pandemic. This is further supported from the Lloyd's Future Set, which estimates global economic losses of between $1.3-4.8 trillion for eruption scenarios ranging from VEI-4 to VEI-7. Given the estimated 450 to 600-year recurrence rate for a VEI-7 event, based on ice core records from periods of deglaciation (Sigl et al., 2022), this would equate to around $2 billion per year (similar to values quoted by the UN; Figure 3). However, as the UN values are based on smaller, more regularly occurring eruptions during the study period, this would be in addition to the $7.6 billion per year quoted ($9.6 billion total). Cassidy & Mani (2022) suggest that investing in crisis preparedness and mitigation would be far cheaper than reacting to a disaster (e.g. Woo et al., 2015), and call for increased attention to, and coordination in, research aimed at forecasting, preparedness and mitigation. The figures from recent eruption events would seem to agree with this perspective, revealing a significant protection gap with economic losses from eruptions regularly reaching billions of dollars while insured losses sit around an order of magnitude lower. This suggests further investment in research for volcanic hazard and loss modelling methods by insurers could be beneficial, provided volcanic hazard models and forecasting capabilities are suitable to provide accurate scientific knowledge to underpin decision-making.

The wider climatic implications of large eruptions

Volcanic emissions, like ash, but especially gases such as sulfur dioxide, and the aerosols they produce, can cause a multi-year cooling shock for large magnitude eruptions. However, there is also evidence to suggest that the radiative changes from aerosol dispersal may have wider implications on climate that could affect 'pre-existing' insurance payouts. Benton et al. (2022) examines climate simulations of radiative changes from volcanic, solar, and land use changes from 850 CE through to the present day, and finds that eruptions with significant aerosol forcing have an impact on the frequency, intensity, and lifetime of hurricanes in their respective hemisphere. Where Northern Hemisphere eruptions cause a reduction in these characteristics for subsequent Northern Hemisphere hurricanes, the opposite occurs in the Southern Hemisphere with eruptions leading to more frequent, intense and longer cyclone seasons. However, work by Andreasen et al. (2024) suggests that climatic impacts of explosive eruptions for the Northern Hemisphere are more complex, with model and ice core evidence suggesting that storminess can increase locally and that extra-tropical cyclones increase in frequency at subtropic and high latitudes while decreasing in mid-latitudes.

With 8 of the 10 biggest insurance payouts of the 20th and 21st centuries resulting from Northern Hemisphere hurricanes (Aon, 2024), these results suggest that a significant volcanic eruption from somewhere like Iceland, Italy, Japan or Central America could re-shape the insurance market in subsequent years. Similarly, an eruption in Indonesia or New Zealand could mean more intense cyclones and increased losses from storm damage, flooding and related impacts in the Southern hemisphere. Liu & Tang (2022) appear to find evidence of this effect for the 2022 Tonga eruption, with aerosol cloud effects seemingly leading to an increase in precipitation and intensity of Tropical Cyclone Cody. However, differing aerosols and eruption column heights appear to have varying effects on climate, with the amount of water vapour also injected into the stratosphere during the Tonga eruption also seeming to have a subtle, yet multi-year net warming effect globally (Jucker et al., 2024).

In addition to effects on hurricane and storm frequencies and intensities, eruptions in the Northern Hemisphere also cause Indian and African monsoons to weaken, increasing the risk of drought (Freychet et al., 2023). Evidence of this can be seen through climate modelling, with Liu et al. (2016) seeing similar volcanic forcing-induced changes in precipitation in the opposite hemisphere to an eruption as can be seen for hurricanes, and Ning et al. (2017) finding CMIP5 simulations showing less Asian Summer Monsoon (ASM) moisture and resulting precipitation during eruption years. However, there is some complexity to these models that requires further study, with Anchukaitis et al. (2010) finding disagreement between General Climate Models (GCMs) and proxy reconstructions of Asian droughts showing wetter conditions over mainland southeast Asia and drier conditions in central Asia during an eruption year. Similar results are also seen by Tejedor et al. (2021), which saw drier conditions over tropical Africa, central Asia and the Middle East, and wetter conditions over much of Oceania and the South American monsoon region in the 1-2 years after tropical volcanic eruptions larger than that of Pinatubo 1991 across the 20th Century. Recent studies have also shown evidence that volcanic eruptions can increase the probability of El Niño onset by up to 98%, by triggering stronger activity of the Madden–Julian oscillation (MJO) in the western Pacific (Kim et al., 2025).

Alongside primary volcanic hazards, these wider climatic impacts are an overlooked threat those in the insurance industry should consider. Changes in intensity and location of extreme weather events caused by volcanic forcing are likely to have profound effects for various industries, such as agriculture (through not only storminess, frosts, flooding and drought, but also lack of photosynthesis from reduction in solar radiation), water companies (decreased rainfall and drought affecting water security) and energy companies (droughts leading to decreased biomass and less water for hydroelectricity, changes in wind patterns, and radiative reduction loss for solar energy).

Although for more mid-sized eruptions these effects may be more localised, they can have cascading impacts on supply chains and financial markets around the world, e.g. by blocking trade chokepoints (Bailey & Wellesley, 2017). Although the direct impacts of an eruption in Indonesia on UK insurance markets would seem minimal, the wider climatic impacts on agriculture, trade, energy and resulting economic inflation would still result in losses.

Volcanic-related extreme weather events may also affect certain parametric insurance schemes meant to protect against the effects of climate change (Ndlovu, 2022), and would have compounding global impacts for years after an eruption that would be significant for the reinsurance industry (Freychet et al., 2023). Mapping out the potential cascading and systemic risks and escalating hazards, as well as modelling climate impacts in real time, would give much better 5 to 10-year forecasts for the reinsurance sector. But this would likely require an international body to govern the response, and to coordinate and distribute reliable data and models.

Regulatory approaches to volcanic risk

Given the potentially ruinous impacts of volcanic disasters, governments and regulatory bodies have taken steps to address volcanic risk within insurance and disaster management frameworks. Public insurance schemes and mandates represent one important approach, especially in volcanically active countries. For example, Iceland established a national Natural Catastrophe Insurance fund in 1975 (after a destructive eruption in Vestmannaeyjar in 1973) to provide compulsory coverage for volcanic eruptions, earthquakes, landslides, avalanches, and floods. By law, all buildings and contents insured against fire in Iceland automatically carry volcano and other catastrophe coverage, ensuring a broad risk pool and financial protection even in the shadow of erupting volcanoes (WFCP, 2018).

New Zealand offers a similar model; under the government-run Earthquake Commission (EQC) scheme, residential properties with fire insurance are automatically covered for volcanic eruption damage (among other natural disasters) up to a certain limit (Stepanova, 2019). This public-private structure has proven crucial; when Mt. Ruapehu erupted in 1995–1996, over 200 insurance claims totalling several million NZD were paid by EQC for ashfall and related damage. Such frameworks illustrate how regulatory policy can secure a baseline of insurance protection for volcanic hazards, spreading risk across society and often backstopping private insurers with government funds or reinsurance.

Outside of these national schemes, regulatory oversight in many insurance markets requires that insurers account for all material catastrophe perils, including volcanic events, in their solvency planning and capital reserves. Under Europe's Solvency II regime, for instance, insurers must identify and quantify their exposure to infrequent but severe events; this implicitly covers volcanic eruptions where relevant, pushing insurers to consider scenario analyses for volcano risk even when standard cat models are lacking. In practice, regulators and rating agencies have flagged volcanic eruption as a "non-modelled peril" that should be stress-tested to avoid unwelcome surprises (Woo & Dalziel, 2023). The Montserrat 1995 loss, described as a "surprise loss for the insurance industry", is a cautionary tale prompting more proactive risk management. Consequently, some insurers now include volcanic eruption scenarios in their internal risk assessments and purchase contingency reinsurance covers (often grouped under all-perils catastrophe treaties).

How can we better model volcanic hazards?

Research efforts have gradually advanced probabilistic volcanic hazard analysis and risk modelling methodologies. By the 2000s, volcanologists had developed statistical models to estimate eruption probabilities and ashfall exceedance probabilities, such as event trees and simulation models for volcanic hazards (Smolka & Käser, 2015). Jenkins et al. (2012) produced notable contributions in probabilistic hazard assessment, and Magill & Blong (2005) proposed simplified risk ranking approaches for pyroclastic flow impacts. Industry-backed modelling initiatives have followed, though slowly. In the mid-2010s, at least one catastrophe modelling firm (RMS) built an advanced probabilistic volcano risk model, but results remained unpublished and proprietary. Overall, the state of volcanic risk modelling is still described as "in its infancy" compared to the mature models for perils like windstorm and earthquake.

Currently, there is little appetite by vendors to model volcanic hazard and its losses. Deterministic models (fully relying on parameter values) can provide retrospective or near real-time modelling. However, in order to forecast hazards and losses before an event occurs, as required by the insurance and reinsurance industries, probabilistic (or stochastic) models are needed to incorporate a degree of randomness in their approach.

Previous attempts to design probabilistic volcanic hazard models for parametric risk transfer products, such as that by Guy Carpenter (Oramas-Dorta et al., 2021) and RMS (Miller, 2007), appear to have either been abandoned or not widely taken up by the insurance industry . The reasons for this are likely due to the relatively low losses from volcanic hazard compared to other natural catastrophes such as earthquakes and wildfires, the uncertainty arising from varying volcanic hazards and their area of influence between differing volcanoes and even subsequent eruptions at the same location, and the costs and computing power required for models incorporating these aspects making them impractical. However, as we see continued improvement in satellite monitoring of volcanoes, high performance computing, AI and deep learning for data processing, and with the potential for volcanic hazards close to critical infrastructure or from large magnitude eruptions to cause significant losses, it may be time to revisit these products.

One example of an institution that currently has some capabilities for probabilistic modelling is the GEM Foundation, following the USAID-funded 'Collaborative Risk Assessment for Volcanoes and Earthquakes (CRAVE) project (GEM Foundation, 2020). This project aimed to develop a common framework for assessment of the impact from earthquakes and volcanoes, with an application in three countries located around the Pacific Rim. This has meant that GEM has some capabilities for loss modelling of volcanic hazards such as ashfall, pyroclastic density currents (PDC), lava flow and lahars, by utilising existing tools for assessment of volcanic hazard: USGS's 'Ash3D' (Yang et al., 2020) and 'LaharZ' (Schilling, 1998) for ashfall and lahar respectively, Buffalo University's 'Titan2D' tool for PDC (Patra et al., 2020), and Vrije Universiteit Brussel's 'Q-LavHA' plugin for lava flow (Mossoux et al., 2016), and linking hazard footprints into OpenQuake in order to calculate loss values from GEM's exposure and vulnerability models. Although functional, these tools are from varying sources and differ in age, and as this method doesn't account for individual volcano characteristics or ongoing unrest influencing the risk of eruption there is still work that could be done to provide more in-depth and comprehensive modelling for these hazards.

An area of current research in this field is the use of satellite imagery, and in particular InSAR, to monitor deformation and gas emission signals at volcanoes as a means of establishing risk from volcanic activity. This is being undertaken by academics at the Centre for the Observation and Monitoring of Volcanoes, Earthquakes and Tectonics (COMET), a NERC-funded community comprising the British Geological Survey and 14 UK universities including Bristol, Leeds and others. Continuous satellite passes provide regularly updated records of current volcano deformation, made available through the COMET Volcano Deformation Portal (Rigby et al., 2021). COMET also examines volcanic degassing through satellite, in particular sulfur dioxide which can be measured globally at unprecedented resolution using the hyperspectral TROPOspheric Monitoring Instrument 'TROPOMI' (Veefkind et al., 2012).

Nevertheless, without subsequent processing and analysis this data is of no use to insurers, and with the sheer amount of data continuously being provided by satellites the man-hours required would be unfeasible. This is where machine learning is being utilised, with deep learning frameworks called Convolutional Neural Networks (CNN) being used to process InSAR using 'transfer learning'. The general applications of AI and machine learning for geohazard assessment may play a central role (Dalziel, 2022), with the specific application of this framework for volcanic risk assessment is discussed by Biggs et al. (2022). This work uses a dataset of ~600,000 automatically processed interferograms covering >1000 volcanoes from 2015-2020. It identified 16 volcanoes with repeated flags for deformation, and of these 5 experienced eruptions, 6 showed slow deformation, 2 had non-volcanic deformation and 3 had atmospheric artefacts. The detection threshold for the whole dataset was 5.9 cm, equivalent to a rate of 1.2 cm/yr over the 5-year study period. This work is helping to identify areas for future improvements, both to the machine learning algorithms themselves as well as processing steps such as atmospheric correction, with the hope that improved reliability can lead to design of a real-time volcano monitoring and alert system through the COMET Portal.

As data quality and processing methods improve, it is possible that these records of InSAR volcano deformation could be compiled and compared against where, when and what particular characteristics of deformation have resulted in historic eruptions within a certain timeframe. This comparison could then be used to inform a probabilistic model of eruptions likely to happen over the next given number of years, and subsequently help form a "forecast based finance" for insurers. If a functional global network such as the World Organisation of Volcano Observatories (INGV, 2019) was able to collate this alongside seismicity and other ground-based modelling methods, standardising data and alert levels globally, this could also be highly valuable to industries such as airlines.

But although work such as COMET's is useful for helping to forecast if, when and where a volcano may erupt, this doesn't provide more detail on the hazard footprints themselves. Work by Biass et al. (2024) examines how assessment of large-scale population exposure to volcanic hazard usually relies on the use of circular footprints, and that this can under or overestimate hazard extent. This is where work such as that by the Corpora for Volcanoes (CorVo) project may be able to offer more insight. This aims to build an innovative tool for volcanic risk forecasting, impact assessment, and resilience planning, by developing an interface to query bodies of digitised documents containing extensive descriptions of past volcanic activity (Principe & Marini, 2023). This approach is currently being prototyped using documents from the BIBV Database for Mount Vesuvius in Italy (IGG, 2021), but hopes to be extended to other volcanoes in multi-hazard settings.

Tools such as CorVo could therefore allow insurers to quickly obtain important information from past eruptive scenarios, such as precursors, specific hazards, hazard footprints and damage caused, as well as social impact and reactions from government and other institutions. By detailing historic eruption types and characteristics, and combining with a probabilistic model using processed satellite data such as from COMET, this could mean the capability to predict what future eruptions may look like at high-risk volcanoes (or close analogues, where insufficient historic information exists) and categorise risks to account for hazards such as lahars, lava flows, PDCs and ash clouds in more detail than currently available methods. Although these fields of research are somewhat disparate, both warrant further investigation and funding in the pursuit of a comprehensive, detailed and reliable framework for forecast-focussed insurance products.

Other examples of initiatives aimed at modelling and reducing volcanic risks include 'Myriad-EU', a European Union Horizon 2020 research project aiming to assess trade-offs and synergies between economic sectors, hazards and their scales for the purposes of disaster risk reduction. Barcelona-based risk intelligence company Mitiga Solutions has also worked with the Danish Red Cross to develop a catastrophe bond for volcanic risk, with the opportunity for wider adoption within the insurance sector. Institutions such as these, the Global Earthquake Model, COMET, and the WTW Research Network exist to bring together academic researchers, NGOs and institutions from across disciplines and geographies, and could help facilitate the collation of databases and recourses necessary to shape such a product.

Another example of such an organisation is the new non-profit Global Volcano Risk Alliance (GVRA), comprising international volcano scientists from academia, volcano observatories, humanitarian groups and other organisations. The GVRA seeks to build global resilience to volcanic eruptions through advocacy and investment in preparedness, monitoring, skillsets and education. Similarly, the now defunct 'Global Volcano Model' (GVM) served a similar purpose of bringing together public and private institutions and organisations, with the collective aim of identifying and reducing risk in volcanic environments. The outcomes of developing GVM included the first Global Volcanic Hazard and Risk analysis for the UN Global Assessment Report in 2015 (Loughlin et al., 2015). Although the GVM has since fallen out of use due to academic bodies not maintaining domain fees, using such networks as a vehicle to collect data and unify research from different institutions with the aim of creating a single probabilistic model for forecasting volcanic hazards and losses could be an investment that reaps rewards for the insurance industry in the same way past work has for earthquakes, landslides, tsunamis and other natural hazards.

Future research is needed to better characterize the frequency and impacts of extreme scenarios, for example through paleo-volcanic studies and improved simulation of climate and supply-chain effects. Closing this knowledge gap would help define the "limits of insurability" for volcanic disasters in a more systematic way (Smolka & Käser, 2015), perhaps informing the design of event caps or industry pools for ultra-catastrophic events.

There is also a gap in insurance coverage and product innovation. Most volcanic losses worldwide still go uninsured, particularly in developing countries around the Pacific "Ring of Fire." Low insurance penetration means communities bear the brunt of recovery costs, reinforcing poverty and vulnerability cycles. Expanding access to affordable volcanic risk insurance (or alternative risk transfer) is a key future direction. This could involve microinsurance products for farmers affected by ashfall, regional risk pools for countries facing similar volcano threats, or multi-peril policies that bundle volcanic eruption with more common risks.

Conclusion

With more than 14% of the world's population living within 100km of an 'active' Holocene volcano, and global exposure set to increase above the average rate of population growth in the coming years, the risk of significant human and monetary losses from volcanic hazards is not to be ignored. Although there have been continued advances in probabilistic volcanic hazard analysis and risk modelling in recent years, many insurers, reinsurers and model vendors have shown little interest in developing their capabilities beyond basic analysis due to the relatively low loss values when compared to other natural hazards such as hurricanes and earthquakes. Economic losses from volcanoes have averaged around $7.6 billion per year in the past three decades, but historical analogues of the largest eruptions in recorded history suggest that a large, VEI-6+ 'fat-tailed' eruption event could cost tens of billions. In addition to the 'primary' hazard from volcanic eruption products like pyroclastic density currents and lava flows, ash and volcanic aerosols have the potential to disrupt supply chains, agriculture, transport networks and infrastructure, and even to influence weather patterns and change the location, timing or intensity of hurricanes, monsoons and droughts.

With these potential impacts in mind, it becomes clear that continued research and innovation is required, not only by academic and industry bodies, but through a joined-up approach with insurers and reinsurers, in order to better incorporate volcanic hazards and their cascading effects into extreme event scenarios. This would serve to not only close a knowledge gap within risk modelling frameworks, but also could help develop products to close the protection gap for vulnerable communities.

References

Anchukaitis, K.J., Buckley, B.M., Cook, E.R., Cook, B.I., D'Arrigo, R.D. & Ammann, C.M. (2010). Influence of volcanic eruptions on the climate of the Asian monsoon region. Geophysical Research Letters, 37(22). Available at: doi.org/10.1029/2010GL044843 (Accessed: 14/04/2025).

Aon (2024). Climate and Catastrophe Insight. Available at: assets.aon.com/-/media/files/aon/reports/2024/climate-and-catastrophe-insights-report.pdf (Accessed 29/01/2025).

Bailey, R. & Wellesley, L. (2017). Chokepoints and Vulnerabilities in Global Food Trade. Chatham House Report. ISBN: 978-1-78413-230-9. Available at: www.chathamhouse.org/sites/default/files/publications/research/2017-06-27-chokepoints-vulnerabilities-global-food-trade-bailey-wellesley-final.pdf (Accessed 24/03/2025).

Benton, B.N., Alessi, M.J., Herrera, D.A., Li, X., Carrillo, C.M. & Ault, T.R. (2022). Minor impacts of major volcanic eruptions on hurricanes in dynamically-downscaled last millennium simulations. Climate Dynamics, 59(5), 1597-1615. Available at: doi.org/10.1007/s00382-021-06057-4 (Accessed: 14/04/2025).

Biass, S., Jenkins, S.F., Hayes, J.L., Williams, G.T., Meredith, E.S., Tennant, E., Yang, Q., Lerner, G.A., Burgos, V., Syarifuddin, M. & Verolino, A. (2023). How well do concentric radii approximate population exposure to volcanic hazards? Bulletin of volcanology, 86(1), 3. Available at: doi.org/10.1007/s00445-023-01686-5 (Accessed: 14/04/2025).

Biggs, J., Anantrasirichai, P., Albino, F., Lazecký, M. & Maghsoudi, Y. (2022). Large-scale demonstration of machine learning for the detection of volcanic deformation in Sentinel-1 satellite imagery. Bulletin of Volcanology, 84(12), 100. Available at: doi.org/10.1007/s00445-022-01608-x (Accessed: 14/04/2025).

Blau, J. (2010). No premiums for ash. Available at: www.dw.com/en/volcanic-ash-is-too-hot-to-handle-insurers/a-5482554 (Accessed: 06/02/2025).

Blong, R. (2021). Four Global Catastrophic Risks–A Personal View. Frontiers in Earth Science, 9, p.740695. Available at: doi.org/10.3389/feart.2021.740695 (Accessed: 15/04/2025).

Breene, K. (2016). Which was the costliest volcanic eruption in history? Available at: www.weforum.org/stories/2016/05/costliest-volcanic-eruption-in-history/ (Accessed: 04/02/2025).

Brown, S.K., Auker, M.R. & Sparks, R.S.J. (2015a). Populations around Holocene volcanoes and development of a Population Exposure Index. Global volcanic hazards and risk, 223-232. Place of publication: Cambridge University Press. Available at: doi.org/10.1017/CBO9781316276273 (Accessed: 15/04/2025).

Brown, S.K., Sparks, R.S.J. & Jenkins, S.F. (2015b). Global distribution of volcanic threat, in S.C. Loughlin et al. (eds.) Global Volcanic Hazards and Risk, pp. 359–370. Place of publication: Cambridge University Press. Available at: doi.org/10.1017/CBO9781316276273.025 (Accessed: 15/04/2025).

Cabinet Office, Government of Japan (2002). Mt. Fuji Hazard Map Review Committee Interim Report. Available at: www.bousai.go.jp/kazan/fuji_map/pdf/fujihm_ir_hr.pdf (Accessed: 10/02/2025).

Caliro, S., Chiodini, G., Avino, R., Carandente, A., Cuoco, E., Di Vito, M.A., Minopoli, C., Rufino, F., Santi, A., Lages, J. & Mangiacapra, A. (2025). Escalation of caldera unrest indicated by increasing emission of isotopically light sulfur. Nature Geoscience, pp.1-8. Available at: doi.org/10.1038/s41561-024-01632-w (Accessed: 15/04/2025).

Cassidy, M. & Mani, L. (2022). Huge volcanic eruptions: Time to prepare. Nature, 608(7923), 469-471. Available at: doi.org/10.1038/d41586-022-02177-x (Accessed: 15/04/2025).

Cerbai, I. & Principe, C. (1996). BIBV: Bibliography of Historic Activity on Italian Volcanoes. Istituto di geocronologia e geochimica isotopica, n. 6/96. OCLC: 41572806.

County of Hawaiʻi (2019). Kilauea Eruption Recovery: 2018 Eruption. Available at: recovery.hawaiicounty.gov/resources/2018-eruption (Accessed: 06/02/2025).

Dalziel, J.H. (2022). How improvements in earth observation and machine learning are re-shaping earth hazard assessment. Available at: www.wtwco.com/engb/insights/2022/11/how-improvements-in-earth-observation-and-machine-learning-are-re-shaping-earthhazard-assessment (Accessed: 12/02/2025).

De Guzman, E.M. (2005). The Pinatubo eruption of June 1991: The nature and impact of the disaster. Available at: www.adrc.asia/publications/recovery_reports/Pinatubo.pdf (Accessed: 06/02/2025).

EM-DAT, CRED/UCLouvain (Last updated 2023). Public EM-DAT Platform. Available at: public.emdat.be/data (Accessed 10/02/2025).

Ferrara, S., Selva, J., Sandri, L., Marzocchi, W., Acocella, V., Bagagli, M., Bianco, F., Borgstrom, S., Caliro, S., Capaccioni, B. & Castellano, M. (2025). Forecasting the evolution of the current unrest of Campi Flegrei by defining anomalies through experts' elicitation. Annals of Geophysics, 68. Available at: doi.org/10.4401/ag-9148 (Accessed: 15/04/2025).

Freire, S., Florczyk, A.J., Pesaresi, M. & Sliuzas, R. (2019). An improved global analysis of population distribution in proximity to active volcanoes, 1975–2015. ISPRS International Journal of Geo-information, 8(8), 341. Available at: doi.org/10.3390/ijgi8080341 (Accessed: 15/04/2025).

Freychet, N., Schurer, A.P., Ballinger, A.P., Suarez-Gutierrez, L. & Timmreck, C. (2023). Assessing the impact of very large volcanic eruptions on the risk of extreme climate events. Environmental Research: Climate, 2(3), 035015. Available at: doi.org/10.1088/2752-5295/acee9f (Accessed: 15/04/2025).

Fujita, E., Kozono, T., Ueda, H., Kohno, Y., Yoshioka, S., Toda, N., Kikuchi, A. & Ida, Y. (2013). Stress field change around the Mount Fuji volcano magma system caused by the Tohoku megathrust earthquake, Japan. Bulletin of Volcanology, 75, 1-14. Available at: doi.org/10.1007/s00445-012-0679-9 (Accessed 15/04/2025).

GEM Foundation (2020). Final Report to USAID /OFDA for: CRAVE-Collaborative Risk Assessment for Volcanoes & Earthquakes. Available at: cloud-storage.globalquakemodel.org/public/wix-new-website/pdf-collections-wix/publications/USAID_CRAVE_Final%20Progress_Report-20200203.pdf (Accessed: 12/02/2025).

HM Government (2023). National Risk Register, 2023 Edition. Available at: assets.publishing.service.gov.uk/media/64ca1dfe19f5622669f3c1b1/2023_NATIONAL_RISK_REGISTER_NRR.pdf (Accessed 11/02/2025).

IATA Economics (2010). IATA Economic Briefing: The impact of Eyjafjallajökull's volcanic ash plume. Available at: www.iata.org/en/iata-repository/publications/economic-reports/impact-of-ash-plume/ (Accessed: 06/02/2025).

Institute of Geosciences and Earth Resources (IGG) (2021). Historical bibliography of active Italian volcanoes. Available at: geca-cnr.ge.imati.cnr.it/pisa/vulcani/make_home_page.php?status=backhome&language=ITA&view=RBI (Accessed: 12/02/2025).

Jenkins, S., Magill, C., McAneney, J. & Blong, R. (2012). Regional ash fall hazard I: a probabilistic assessment methodology. Bulletin of volcanology, 74, pp.1699-1712. Available at: doi.org/10.1007/s00445-012-0627-8 (Accessed: 15/04/2025).

Jenkins, S.F., Biass, S., Williams, G.T., Hayes, J.L., Tennant, E., Yang, Q., Burgos, V., Meredith, E.S., Lerner, G.A., Syarifuddin, M. & Verolino, A. (2022). Evaluating and ranking Southeast Asia's exposure to explosive volcanic hazards. Nat. Hazards Earth Syst. Sci., 22, 1233–1265. Available at: doi.org/10.5194/nhess-22-1233-2022 (Accessed: 15/04/2025).

Jenkins, S.F., Mee, K., Engwell, S.L., Loughlin, S.C., Faria, B.V.E., Yirgu, G., Bekele, Y., Lewi, E., Vye-Brown, C., Fraser, S.A. & Day, S.J. (2024). Assessing volcanic hazard and exposure in a data poor context: Case study for Ethiopia, Kenya, and Cabo Verde. Progress in Disaster Science, 23, 100350. Available at: doi.org/10.1016/j.pdisas.2024.100350 (Accessed: 15/04/2025).

Jucker, M., Lucas, C. & Dutta, D. (2024). Long-Term Climate Impacts of Large Stratospheric Water Vapor Perturbations. Journal of Climate, 37, 4507–4521. Available at: doi.org/10.1175/JCLI-D-23-0437.1 (Accessed: 15/04/2025).

Käser, M. & Rauch, E. (2022). Volcanic eruptions – The earth’s ring of fire. Available at: www.munichre.com/en/risks/natural-disasters/volcanic-eruptions.html (Accessed: 04/02/2025).

Kilburn, C.R.J., Carlino, S., Danesi, S. & Pino, N.A. (2023). Potential for rupture before eruption at Campi Flegrei caldera, Southern Italy. Commun Earth Environ 4, 190. Available at: doi.org/10.1038/s43247-023-00842-1 (Accessed: 15/04/2025).

Kim, H., Min, S.K., Kim, D. & Visioni, D. (2025). Volcanically forced Madden–Julian oscillation triggers the immediate onset of El Niño. Nature Communications, 16(1), p.1399. Available at: doi.org/10.1038/s41467-025-56692-2 (Accessed: 15/04/2025).

Liu, F., Chai, J., Wang, B., Liu, J., Zhang, X. & Wang, Z. (2016). Global monsoon precipitation responses to large volcanic eruptions. Scientific reports, 6(1), 24331. Available at: doi.org/10.1038/srep24331 (Accessed: 15/04/2025).

Liu, H., & Tang, X. (2022). Tongan volcanic eruption intensifies tropical cyclone Cody (2022). Frontiers in Earth Science, 10, 904128. Available at: doi.org/10.3389/feart.2022.904128 (Accessed: 15/04/2025).

Lloyds & Cambridge Centre for Risk Studies (2024). Lifting the lid on volcanic risk. Available at: www.lloyds.com/news-and-insights/futureset/futureset-insights/systemic-risk-scenarios/volcanic-eruption (Accessed: 04/02/2025).

Lockwood, J.P. & Hazlett, R.W. (2010). Chapter 6: effusive volcanic eruptions and their products. Volcanoes: global perspectives, Wiley-Blackwell (Chichester), 127-172. ISBN: 978-1-405-16249-4

Loughlin, S.C., Sparks, R.S.J., Brown, S.K., Jenkins, S.F. & Vye-Brown, C. eds. (2015). Global volcanic hazards and risk. Place of publication: Cambridge University Press. ISBN: 978-1-316-27627-3. Available at: doi.org/10.1017/CBO9781316276273 (Accessed: 15/04/2025).

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. & Wanner, H. (2004). European seasonal and annual temperature variability, trends, and extremes since 1500. Science, 303(5663), 1499-1503. Available at: doi.org/10.1126/science.1093877 (Accessed: 15/04/2025).

Magill, C. & Blong, R. (2005). Volcanic risk ranking for Auckland, New Zealand. II: Hazard consequences and risk calculation. Bulletin of volcanology, 67, pp.340-349. Available at: doi.org/10.1007/s00445-004-0375-5 (Accessed: 15/04/2025).

Magill, C., Blong, R. & McAneney, J. (2006). VolcaNZ—A volcanic loss model for Auckland, New Zealand. Journal of Volcanology and Geothermal Research, 149(3-4), 329-345. Available at: doi.org/10.1016/j.jvolgeores.2005.09.004 (Accessed 15/04/2025).

Mahalingam, A., Coburn, A., Jung, C.J., Yeo, J.Z., Cooper, G. & Evan, T. (2018). Impacts of severe natural catastrophes on financial markets. Cambridge Centre for Risk Studies. Available at: www.jbs.cam.ac.uk/wp-content/uploads/2020/08/crs-impacts-of-severe-natural-catastrophes-on-financial-markets.pdf (Accessed: 11/02/2025).

Mani, L., Tzachor, A. & Cole, P. (2021). Global catastrophic risk from lower magnitude volcanic eruptions. Nature Communications, 12, 4756. doi.org/10.1038/s41467-021-25021-8

Miller, R. (2007). Model to quantify volcano risk. Available at: www.businessinsurance.com/model-to-quantify-volcano-risk/ (Accessed: 04/02/2025).

Mossoux, S., Saey, M., Bartolini, S., Poppe, S., Canters, F. & Kervyn, M. (2016). Q-LAVHA: A flexible GIS plugin to simulate lava flows. Comput. Geosci., 97, 98–109. Available at: doi.org/10.1016/j.cageo.2016.09.003 (Accessed: 15/04/2025).

National Institute of Geophysics and Volcanology (INGV) (2019). World Organisation of Volcano Observatories. Available at: wovo.iavceivolcano.org/ (Accessed: 12/02/2025).

Ndlovu, L. (2022). Parametric insurance: an effective tool in helping Africa fight climate change. Available at: www.preventionweb.net/news/parametric-insurance-effective-tool-helping-africa-fight-climate-change (Accessed: 11/02/2025).

Ning, L., Liu, J. & Sun, W. (2017). Influences of volcano eruptions on Asian Summer Monsoon over the last 110 years. Scientific Reports, 7(1), 42626. doi.org/10.1038/srep42626

OECD (2024). Global Insurance Market Trends 2024. OECD Publishing, Paris. Available at: doi.org/10.1787/5b740371-en (Accessed: 15/04/2025).

Oppenheimer, C. (2003). Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. Progress in physical geography, 27(2), pp.230-259. Available at: doi.org/10.1191/0309133303pp379ra (Accessed: 15/04/2025).

Oppenheimer, C. (2011). Eruptions that shook the world. Cambridge University Press. ISBN: 978-0-521-64112-8

Oramas-Dorta, D., Tirabassi, G., Franco, G. & Magill, C. (2021). Design of parametric risk transfer solutions for volcanic eruptions: an application to Japanese volcanoes. Natural Hazards and Earth System Sciences, 21(1), 99-113. Available at: doi.org/10.5194/nhess-21-99-2021 (Accessed: 15/04/2025).

Patra, A., Bevilacqua, A., Akhavan-Safaei, A., Pitman, E. B., Bursik, M. & Hyman, D. (2020). Comparative analysis of the structures and outcomes of geophysical flow models and modeling assumptions using uncertainty quantification. Frontiers in Earth Science, 8. Available at: doi.org/10.3389/feart.2020.00275 (Accessed: 15/04/2025).

Perils AG (2024). TRY 117.0bn - PERILS releases fourth industry loss estimate for the Kahramanmaras Earthquake Sequence. Available at: www.perils.org/files/News/2023/Loss-Announcements/A.-Kahramanmaras-Earthquake-Sequence-Feb-2023/2024-02-06-PERILS-Press-Release-Kahramanmaras-Earthquake-Sequence-6-Feb-2023.pdf (Accessed: 04/02/2025).

Principe, C. & Marini, C. (2023). Using text corpora for volcanic eruption impact assessment and resilience planning: The first steps of the CorVo project. Copernicus Meetings, EGU23-15120. Available at: doi.org/10.5194/egusphere-egu23-15120 (Accessed: 15/04/2025).

Puma, M., Chon, S. & Wada, Y. (2015). Exploring the potential impacts of historic volcanic eruptions on the contemporary global food system. Past Global Changes Magazine, 23(2), 66–67. Available at: doi.org/10.22498/pages.23.2.66 (Accessed: 15/04/2025).

Raible, C.C., Brönnimann, S., Auchmann, R., Brohan, P., Frölicher, T.L., Graf, H.F., Jones, P., Luterbacher, J., Muthers, S., Neukom, R. & Robock, A. (2016). Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects. Wiley Interdisciplinary Reviews: Climate Change, 7(4), pp.569-589. Available at: doi.org/10.1002/wcc.407 (Accessed: 15/04/2025).

Rigby, R., Burns, H., Watson, C.S., Lazecky, M., Ebmeier, S., Morishita, Y., Maghsoudi Mehrani, Y., Elliott, J. & Wright, T. (2021). COMET_VolcDB: COMET Volcanic and Magmatic Deformation Portal (2021 beta release) (1.1-beta). Zenodo. Available at: doi.org/10.5281/zenodo.4545877 (Accessed: 15/04/2025).

Rees, J., Loughlin, S., Tappin, D., England, P., Petley, D., Barclay, J. & McCloskey, J. (2012). Anticipation of Geophysical Hazards. Available at: assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/409257/12-1301-anticipation-of-geophysical-hazards.pdf (Accessed 11/02/2025).

Rubert, J.A. (2021). The volcano of La Palma, a month later: 450 million euros in losses and more than 800 hectares razed. Available at: www.cope.es/emisoras/canarias/santa-cruz-de-tenerife/la-palma/noticias/volcan-palma-mes-despues-450-millones-euros-perdidas-mas-800-hectareas-arrasadas-20211018_1565495 (Accessed: 07/02/2025).

Schilling, S.P. (1998). LAHARZ; GIS programs for automated mapping of lahar-inundation hazard zones. U.S. Geological Survey Open-File Report 98-638. Available at: doi.org/10.3133/ofr98638 (Accessed: 15/04/2025).

Schmidt, A., Ostro, B., Carslaw, K.S., Wilson, M., Thordarson, T., Mann, G.W. & Simmons, A.J. (2011). Excess mortality in Europe following a future Laki-style Icelandic eruption. Proceedings of the National Academy of Sciences, 108(38), 15710-15715. Available at: doi.org/10.1073/pnas.1108569108 (Accessed: 15/04/2025).

Seaberry, J. (1980). Mt. St. Helens Blows $1 Billion. Available at: www.washingtonpost.com/archive/business/1980/09/16/mt-st-helens-blows-1-billion/750edf2c-7501-44f9-ae6f-5193613a5be2/ (Accessed: 04/02/2025).

Sigl, M., Toohey, M., McConnell, J.R., Cole-Dai, J. & Severi, M. (2022). Volcanic stratospheric sulfur injections and aerosol optical depth during the Holocene (past 11 500 years) from a bipolar ice-core array. Earth System Science Data, 14(7), 3167-3196. Available at: doi.org/10.5194/essd-14-3167-2022 (Accessed: 15/04/2025).

Smolka, A. & Käser, M. (2015). Volcanic Risks and Insurance. In Volcanic Hazards, Risks and Disasters (pp. 301-314). Elsevier. doi.org/10.1016/B978-0-12-396453-3.00012-5

Spence, R., Gunesekara, R. & Zuccaro, G. (2010). Insurance risks from volcanic eruptions in Europe. Available at: bencana-kesehatan.net/arsip/images/referensi/artikel/Insurance%20Risks%20from%20Volcanic%20Eruptions_Final.pdf (Accessed: 18/10/2024).

Statistics Iceland (2023). Profits in agriculture triple while the number of farms continues to decline. Available at: statice.is/publications/news-archive/enterprises/income-statement-and-balance-sheet-for-agriculture-11758/ (Accessed: 10/02/2025).

Stepanova, K. (2019). Ring of fire: a deep dive into New Zealand's volcanic risks. Available at: www.insurancebusinessmag.com/nz/news/breaking-news/ring-of-fire-a-deep-dive-into-new-zealands-volcanic-risks-189312.aspx (Accessed 24/03/2025).

Strehlow, K. (2023). Breaking Down the Multiple Hazards of Volcanic Eruptions. Available at: www.mitigasolutions.com/insights/breaking-down-the-multiple-hazards-of-volcanic-eruptions (Accessed: 04/03/2025).

Thordarson, T. & Self, S. (2003). Atmospheric and environmental effects of the 1783–1784 Laki eruption: A review and reassessment. Journal of Geophysical Research: Atmospheres, 108(D1), AAC-7. Available at: doi.org/10.1029/2001JD002042 (Accessed: 15/04/2025).

Veefkind, J.P., Aben, I., McMullan, K., Förster, H., De Vries, J., Otter, G., Claas, J., Eskes, H.J., De Haan, J.F., Kleipool, Q. & Van Weele, M. (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Remote sensing of environment, 120, pp.70-83. Available at: doi.org/10.1016/j.rse.2011.09.027 (Accessed: 15/04/2025).

Venzke, E. (2024). Global Volcanism Program Volcanoes of the World Database (v. 5.2.5; 23 Dec 2024). Distributed by Smithsonian Institution. Available at: doi.org/10.5479/si.GVP.VOTW5-2024.5.2 (Accessed: 15/04/2025).

Verisk Analytics Inc. (2024). Verisk 2024 Global Modeled Catastrophe Losses. Available at: www.verisk.com/company/newsroom/new-report-average-annual-natural-catastrophe-losses-for-the-insurance-industry-reaches-new-high-of-$151-billion/ (Accessed: 05/09/2024).

Verisk Extreme Event Solutions (2023). Verisk Estimates Economic Losses from February 6 Earthquakes in Turkey Likely to Exceed USD 20 Billion. Available at:

www.verisk.com/company/newsroom/verisk-estimates-economic-losses-from-february-6-earthquakes-in-turkey--likely-to-exceed-usd-20-billion/ (Accessed: 07/02/2025).

Waradi, V. & Perry, T. (2022). Additional $20 million for Disaster Recovery and Economic Reform in Tonga. Available at: www.worldbank.org/en/news/press-release/2022/06/15/additional-20-million-for-disaster-recovery-and-economic-reform-in-tonga?_gl=1*1mgfkbg*_gcl_au*MjAzNzQ4MDk4NC4xNzIzNjI1NDQ5 (Accessed: 07/02/2025).

Wilson, T.M., Stewart, C., Sword-Daniels, V., Leonard, G.S., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G. & Barnard, S.T. (2012). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, Parts a/b/c, 45, pp.5-23. Available at: doi.org/10.1016/j.pce.2011.06.006 (Accessed: 15/04/2025).

Wilson, T.M., Jenkins, S. & Stewart, C. (2015). Impacts from volcanic ash fall. In Volcanic Hazards, Risks and Disasters. Elsevier, 47-86. Available at: doi.org/10.1016/B978-0-12-396453-3.00003-4 (Accessed: 15/04/2025).

Woo, G. (2015). Cost–benefit analysis in volcanic risk. In Volcanic hazards, risks and disasters (pp. 289-300). Elsevier. Available at: doi.org/10.1016/B978-0-12-396453-3.00011-3 (Accessed: 15/04/2025).

Woo, G. & Dalziel, J.H. (2023). Volcanic risk and insurance: The untapped potential of downward counterfactual perspectives. Available at: www.wtwco.com/en-gb/insights/2023/11/volcanic-risk-and-insurance-the-untapped-potential-of-downward-counterfactual-perspectives (Accessed 24/03/2025).

World Forum of Catastrophe Programs (2018). Natural Catastrophe Insurance of Iceland (NTI) Description. Available at: www.wfcatprogrammes.com/iceland-description (Accessed: 24/03/2025).

Yang, Q., Pitman, E.B., Spiller, E., Bursik, M. & Bevilacqua, A. (2020). Novel statistical emulator construction for volcanic ash transport model Ash3d with physically motivated measures. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 476(2242):20200161. Available at: dx.doi.org/10.1098/rspa.2020.0161 (Accessed: 15/04/2025).

ZMS Cable (2022). Tonga Submarine Fiber Optic Cable Repair May Take 5 Months Overall Cost More Than 1 Million U.S. Dollars. Available at: kvcable.com/tonga-submarine-fiber-optic-cable-repair-may-take-5-months-overall-cost-more-than-1-million-u-s-dollars/#:~:text=zms%40kvcable.com-

,Tonga%20Submarine%20Fiber%20Optic%20Cable%20Repair%20May%20Take%205%20Months,Than%201%20Million%20U.S.%20Dollars (Accessed: 07/02/2025).