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

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Abstract

Within (re)insurance, volcanic hazards are often overlooked due to long return periods and low financial losses from historic events compared to geohazards such as earthquakes. However, with continued population growth increasing exposure, and sophisticated monitoring and modelling revealing the extent of volcanic hazards and secondary effects, these perils should be thoroughly considered. This review and synthesis paper explores population exposure to active Holocene volcanoes, compares economic and insured losses of significant eruptions, and explores how past event analogues could affect the modern world. The past 40 years have mostly seen eruptions of Volcanic Explosivity Index (VEI)-3–4; significant but not “super-catastrophes.” Should a VEI-5+ event affect a densely populated area or country with high insurance penetration, losses could be significant. Countries with the highest exposed populations to volcanoes differ from countries at greatest risk of insurable losses, with lower insurance penetration in more exposed countries identifying a protection gap. Eruptions in smaller nations show financial vulnerability, with eruptions leading to large losses proportional to GDP (30-37%). Economic losses of accumulated volcanic activity total \$152.6 billion over 20 years (~\$7.6 billion a year). Research shows that large, long return period, global climate-affecting eruptions could lead to multi-trillion-dollar losses, impacting (re)insurance markets similarly to hurricanes. Therefore, in addition to quantifying loss estimates for future eruption scenarios, we discuss research and industry initiatives to collate volcanic data and model hazards to aid disaster risk reduction, increase preparedness and resilience, facilitating global standardisation of data and risk communication to better prepare (re)insurers for eruptions.

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

Introduction

Within insurance and reinsurance, volcanic risk is not usually a priority of broking conversations. Although discussed amongst natural catastrophes (e.g. Mitchell-Wallace et al. 2017), and both human and economic exposure to volcanoes has been explored (e.g. Spence et al. 2010, Choumert-Nkolo et al. 2021), the insurance industry views large-impact eruptions as less frequent and either less damaging than large magnitude earthquakes, or for the largest eruptions (VEI-7+) so damaging to be considered uninsurable. By comparison, earthquakes occur regularly and globally, and large magnitude events intersecting urban areas with sub-standard building practices can cause devastating and costly results. 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). However, many large urban centres are built around active volcanic centres, especially in south-east Asia and central America where eruption hazards can vary between volcanoes and even phases of a single event with potential for significant losses. Eruptions in exposed locations do not necessarily need to be large, i.e. VEI-5+, to seriously impact urban environments not sufficiently prepared (Mani et al., 2021). Such events are referred to by insurers as 'fat-tailed' or 'global catastrophic' risks; with low probabilities and repeat times, but capable of significant losses with potential to affect multiple countries beyond that of its origin (Blong 2021).

A small body of work has examined volcanic risk from an explicitly financial or insurance perspective. Smolka and Käser (2015) provide the closest approach to this review, assessing insurance mechanisms for volcanic hazards, risk evaluation and modelling, but do not address regulatory frameworks or cascading climatic effects. Spence et al. (2010) explores volcanic impacts on insurance and risk ranking at a regional scale. Choumert-Nkolo et al. (2021) examines the economics of volcanic hazards, mentioning limited insurance coverage in passing. Ormas-Dorta et al. (2021) discusses parametric risk transfer, a specific type of insurance solution, for Japanese ash-producing volcanic settings. Woo (2015) performs cost-benefit analysis for volcanic risk management.

Collectively, this literature treats volcanic hazards as discrete, regionally bounded and primarily physical phenomena, and says little about how eruptions interact with the climate, nor the structure of insurance and reinsurance markets. This paper addresses that gap by assessing exposure and insurability at global rather than regional scale, provides a new perspective of volcano-climate shocks as a mechanism of loss amplification in insurance markets, situates volcanic risk within regulatory and public scheme frameworks that determine whether losses are covered, and identifies the protection gap between countries with the highest human exposure and those with the greatest insurable exposure.

Past attempts to develop volcanic modelling tools 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), have been abandoned or not widely adopted by the industry due to low return periods of high-impact eruptions, the range of possible hazards that could result, and uncertainties

associated with their probability, timing and location. These limitations have the potential to leave insurers unprepared if a high-impact eruption were to occur.

In order to quantify the human and financial risks from volcanoes, data on the relevant hazards, exposure and past events must be analysed. This is achieved through compiling information on characteristics of past high-impact volcanic events and impacts from academic literature, country-level data on economic and population demographics, and studies modelling the potential physical and financial effects of future eruption scenarios. In addition, anecdotal information from insurance and reinsurance representatives obtained through meetings and interviews, in addition to industry-based research publications, helps contextualise current industry views on volcanic risk.

This paper aims to expand upon existing literature by firstly identifying volcanoes that present significant risk, both in terms of human and financial exposure, detailing the range of eruptive and secondary hazards associated with volcanic activity and possible losses based on historical events and analogues, and giving suggestions of how ongoing research can improve monitoring, modelling and forecasting to better quantify risks in order to aid resilience, emergency planning and policymaking.

Exposure to volcanic hazards

Figure 1 shows a comparison of country GDP against Holocene volcanoes with large populations within 30km, commonly used as the footprint for life-threatening explosive eruption hazards such as large-clast ejecta and PDCs (Biass et al. 2023), and confirms the majority of high-risk exposed locations are concentrated in south-east Asia (mostly Indonesia) and Central America (Brown et al. 2015a). With the notable exceptions of Italy and Japan, there are significantly fewer volcanoes with large populations nearby in high GDP economies.

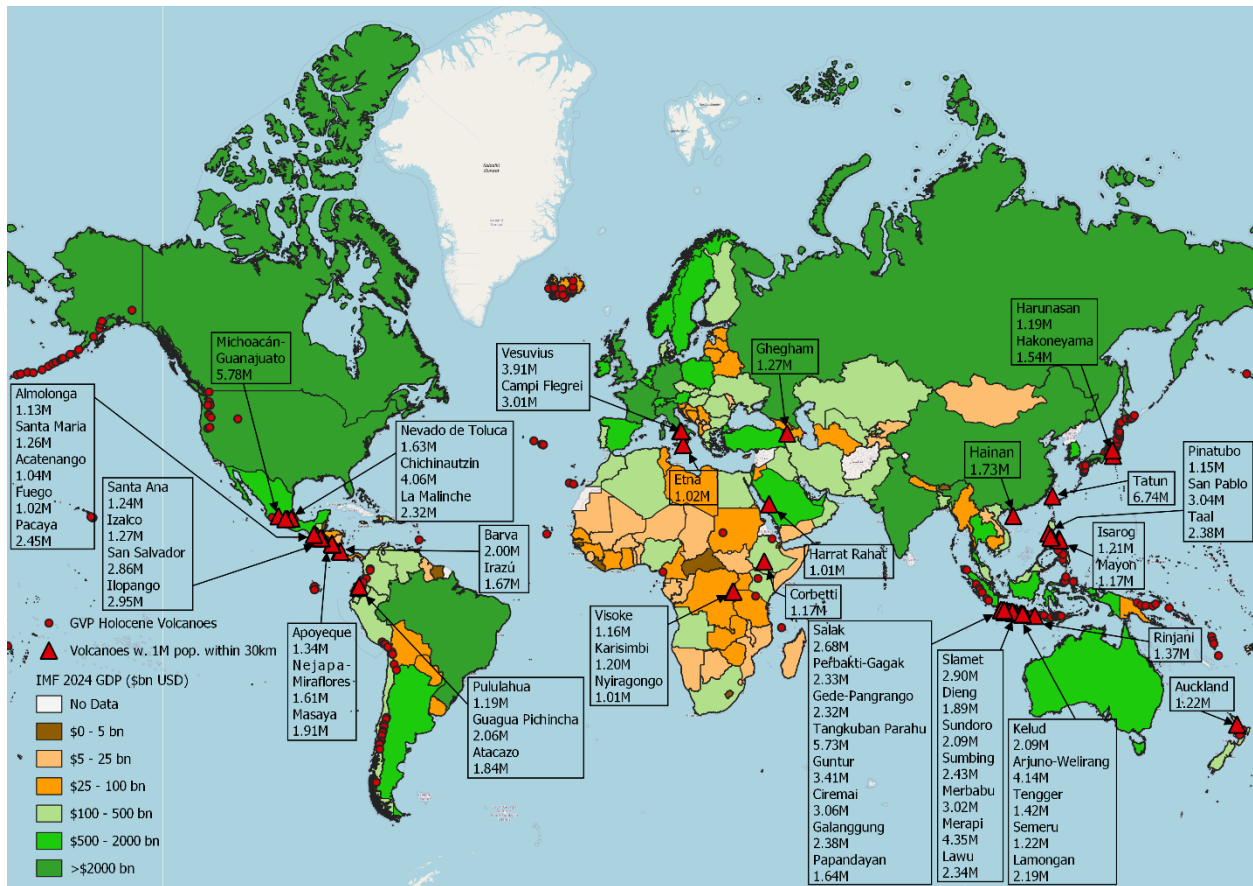


Figure 1: Global distribution of Holocene volcanoes (red dots), with populations of >1 million within a 30 km radius (red triangles). Source: Smithsonian Global Volcanism Program. This includes Indonesia (n=21), Philippines, Guatemala (n=5), Mexico, El Salvador (n=4), Nicaragua, Ecuador, Italy (n=3), 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.

Figure 2 provides insight about relative country-level risk from an insurance perspective, by comparing the number of active Holocene volcanoes (those which have erupted within the last 10,000 years) with total insurance penetration values per country. Insurance penetration is used as an indicator of insurance sector development within a country, 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.

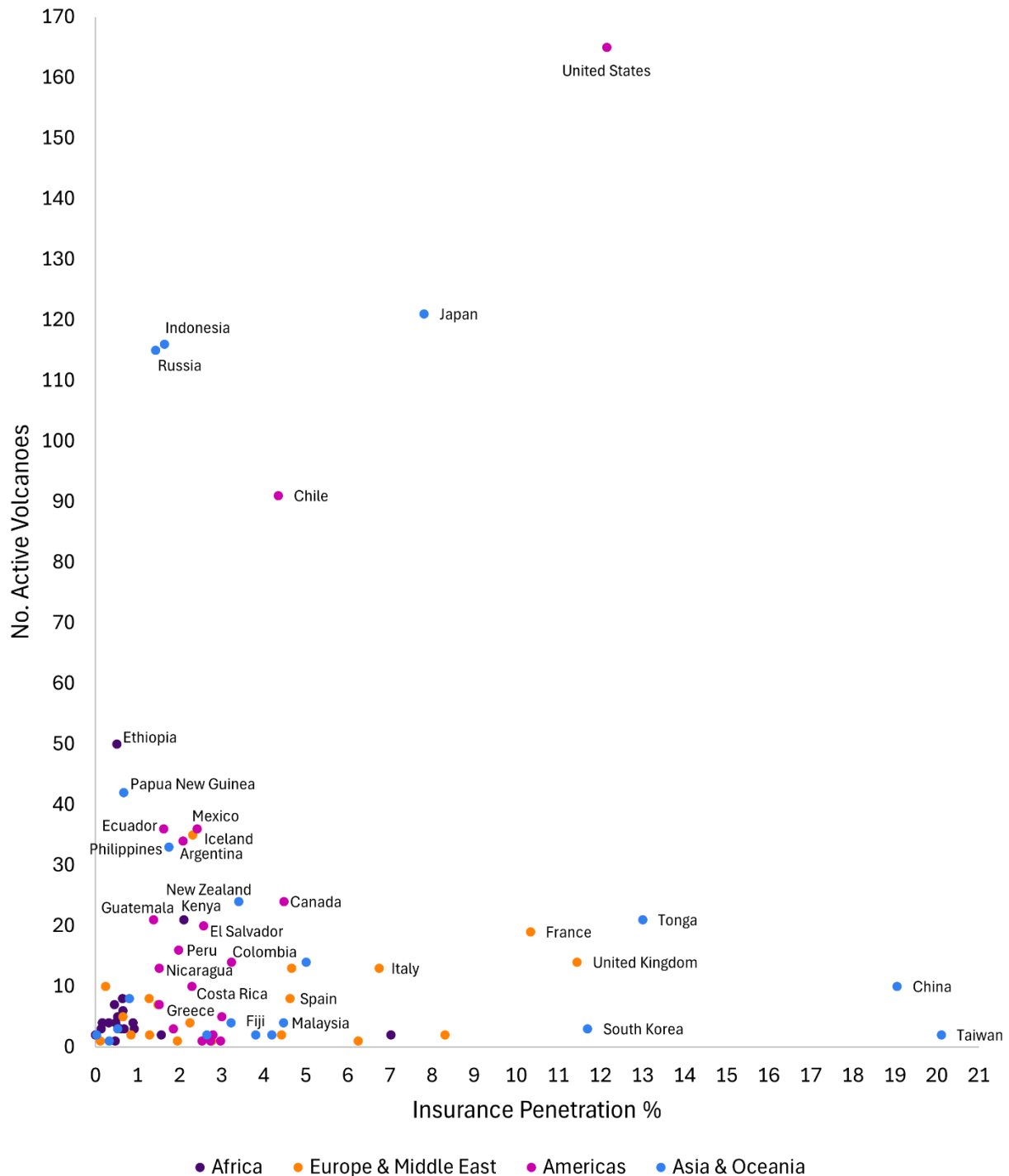


Figure 2: Insurance penetration vs. number of Holocene volcanoes by country. Insurance penetration measures total value of premiums as a percentage of GDP in a given year. Includes overseas territories, e.g. UK and France. Source: Volcano data from Smithsonian Global Volcanism Program, insurance data from OECD, Africa Re & Axco.

This suggests that countries like China and Taiwan have relatively low insurance exposure (high penetration and a lower number of active volcanoes), while countries like Japan, Chile, Indonesia,

Russia and the US are at greater risk of higher insured losses. Countries with a moderate number of volcanoes and very low penetration, such as Ethiopia and Papua New Guinea, are likely to not be covered against a potential volcanic disaster (known by the insurance industry as a 'protection gap').

Examining the data more closely shows that although some countries have fewer volcanoes, urban areas are particularly exposed (e.g. Taipei in Taiwan, or Naples in Italy). Some volcanoes also show increased unrest, such as Campi Flegrei, Italy (e.g. Kilburn et al. 2023). Measurement of crustal stresses, gas ratios and long-term deformation at the volcano suggests possible increased risk of eruption (Ferrara et al. 2025), and given proximity to Naples is a risk that should be considered for losses from business interruption, tourism and air travel disruption (Kilburn et al. 2023, Caliro et al. 2025). A 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 significant proportion of this despite relatively low take-up rate (the number of people or organisations taking out insurance premiums, compared to the total number eligible). According to Lloyd's 'Futureset' tool, an eruption of one of IAVCEI's 16 "Decade Volcanoes" with >48hrs duration, 30km high eruption column, and 5cm+ ash depth across the local area could cost \$14 billion USD (expected economic loss multiplied by probability of occurrence), with global economic impacts reaching a probability weighted average of \$1.6 trillion USD over 5 years across different severity scenarios (Lloyds & CCRS 2024). Details & historic analogues of the Lloyd's Futureset scenarios are shown in Table 1.

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 and economic hubs such as Tokyo (Fujita et al. 2013).

Worldwide, over 1 billion people live within 100 km of an active volcano, over 14.3% of the global population (Freire et al. 2019). Additional volcanoes will have exposed populations in the millions or tens of millions in the coming years, given the increasing population trend. Freire et al. (2019) also notes 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. Mani et al. (2021) identifies seven global 'pinch-points' where convergence of critical infrastructure (such as air traffic, shipping

190 routes and submarine communications cables) mean even a moderately-sized eruption could
191 incur significant losses. These sources demonstrate the global exposure to volcanic hazard.

193 **Relative financial losses from past eruptions**

194 We've reviewed literature that demonstrates how hazards from volcanoes can be variable and
195 wide-reaching, and exposure to these can be significant in parts of the world. From a catastrophe
196 insurance market point of view, the key is comparing insurable losses in a calendar year from
197 currently modelled natural hazards such as windstorm, earthquake & flood events against
198 volcanic eruption (Breene 2016, Verisk 2024). Have any of these volcanic events been 'insurance
199 market defining'? Eruptions are clearly devastating to the countries involved, but how much do
200 they impact loss ratios of the insurance market and how much could they in a worst-case scenario
201 such as those detailed by Lloyd's & CCRS (2024)?

202
203 For the (re)insurance industry, large catastrophic events with high losses tend to act as a catalyst
204 for change, increasing demand for capacity to model and suitably cover similar disasters in future.
205 For example, Hurricane Andrew in 1992 caused approximately \$27 billion in damages (over \$50
206 billion today), \$15.5 billion of which was insured (\$36.9 billion today) (Schwartz & Linkin 2017),
207 leading to the insolvency of several insurance companies unprepared for such massive losses
208 (McChristian 2012). This highlighted the need for better risk management and more substantial
209 financial backing to model such large weather events, as insurers realized their exposure to these
210 was greater than previously estimated. Following this, there was a significant increase in demand
211 for reinsurance as primary insurers sought to protect themselves against similar future events,
212 and increasingly now in the face of anthropogenic climate change, resulting in growth for the
213 reinsurance market as more companies entered the space and existing reinsurers expanded their
214 capacity. It could be argued that there have been fewer similarly large precedents set for volcanic
215 catastrophes, meaning that the insurance industry is unprepared for the form and extent of losses
216 from such events.

217
218 The United Nations assessed the economic damage caused by all types of natural disasters
219 between 1995 and 2015, and found that geophysical disasters (volcanoes and earthquakes)
220 costed \$763 billion during that period (Breene 2016) (Figure 3). Of these disasters, 20% were
221 volcanic, putting the cost of volcanic activity at \$152.6 billion over 20 years (or an average of \$7.6
222 billion a year).

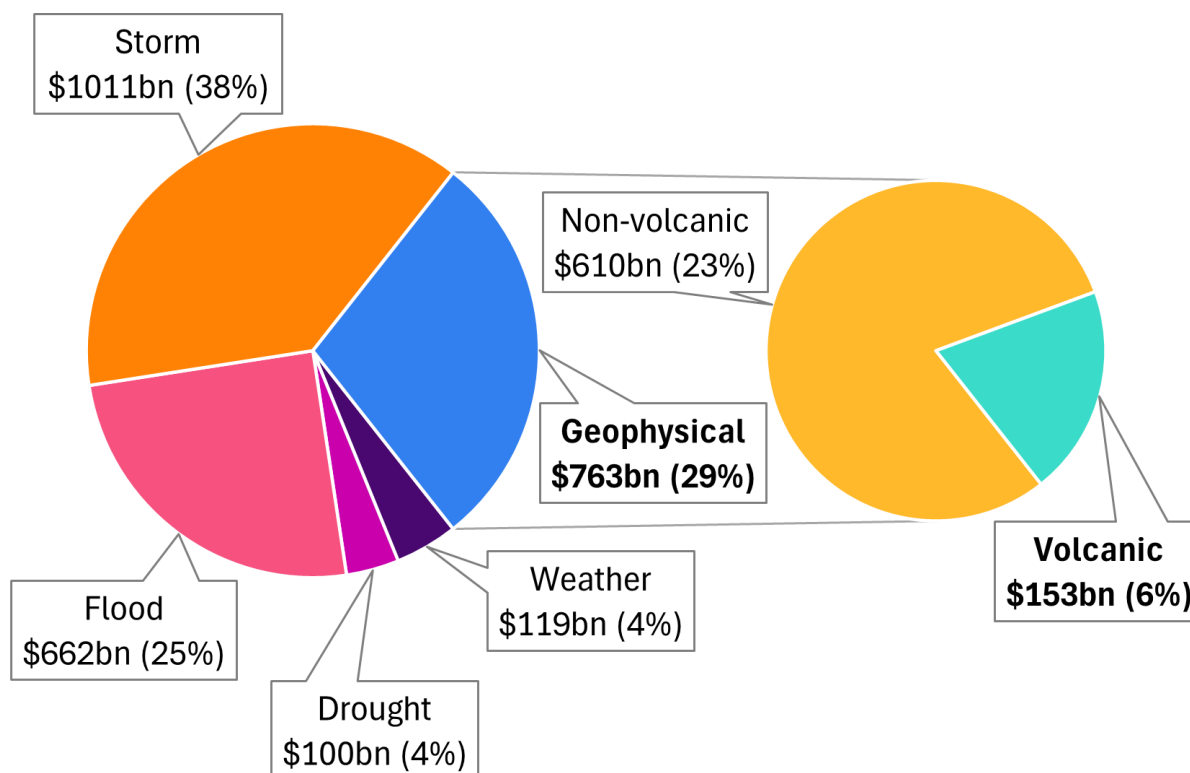
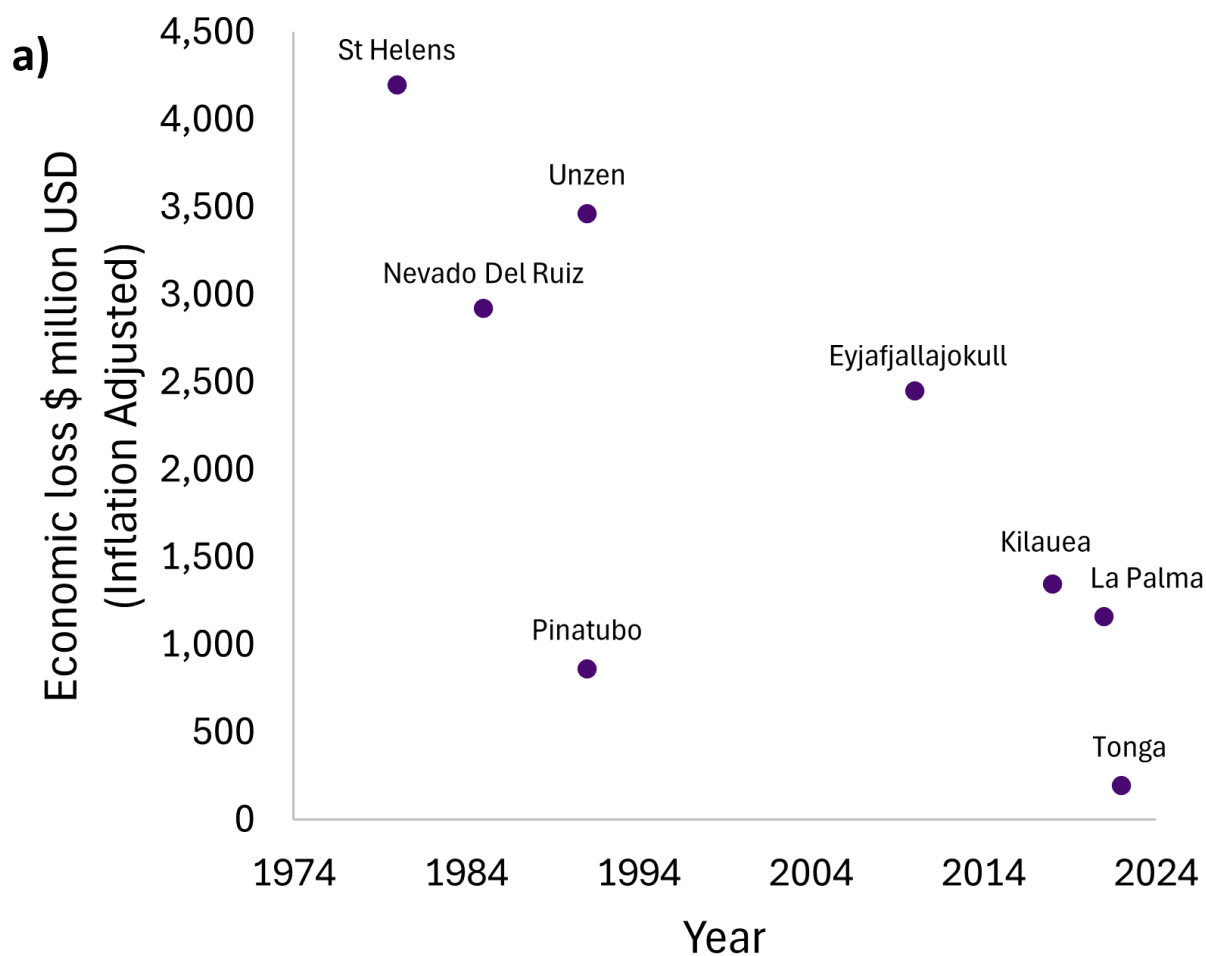


Figure 3: Economic damage by natural disaster type, 1995-2015. Source: United Nations International Strategy for Disaster Reduction.

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 shown in Figure 3 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.

Values 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 (\$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 4a). Other significant losses from eruptions include Mount St Helens (1980); although quoted by Munich Re as having \$860 million in economic losses and \$30 million insured losses, in the months after the event the Washington Post 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 filed, 166 recovery loans applied for and \$215 million USD (\$744 million adjusted for

inflation) spent on dredging rivers that year (Rees et al. 2012). According to figures by International Disaster Database EM-DAT, Nevado Del Ruiz in Columbia (1985) also had total economic losses of \$1 billion (\$2.9 billion adjusted for inflation), and 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 the total economic loss for the airline industry from Eyjafjallajökull (2010) was around \$1.7 billion (\$2.5 billion adjusted for inflation) (IATA 2010) (Figure 4a). Moreover, many affected airlines weren't insured against loss of revenue from 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 total loss value divided by number of eruptions to give average loss per eruption (Figure 4b).



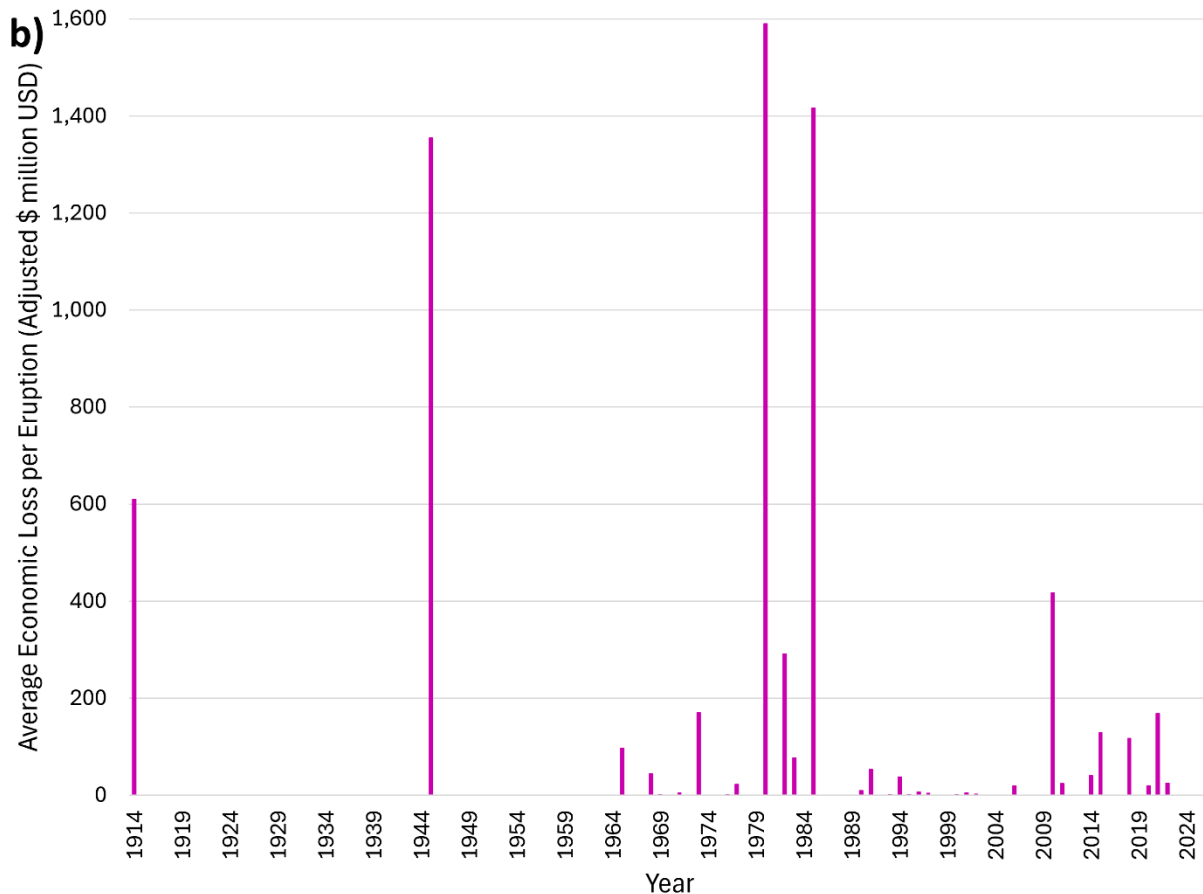


Figure 4: a) Inflation-adjusted economic loss from eruptions in the past 50 years: St. Helens 1980, \$4.2b (Seaberry 1980), Nevado Del Ruiz 1985, \$2.9b (EM-DAT 2023), Pinatubo 1991, \$0.9b (De Guzman 2005), Unzen 1990-1995, \$3.5b (Käser & Rauch 2022), Eyjafjallajökull 2010, \$2.5b (IATA 2010), Kilauea 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 (where data available), 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 GDP impact of the 2021 La Palma eruption was over 30% (Rubert 2021). The 2022 Hunga Tonga–Hunga Ha'apai eruption, 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, 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 (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.

Reviewing this data demonstrates that although most eruptions incur economic and insured losses one to two orders of magnitude lower than other natural catastrophe events considered 'market-defining', GDP impact can vary significantly between countries. If an eruption the size of 2022 Hunga Tonga–Hunga Ha'apai were to occur in a populous region such as Central America

or south-east Asia (identified in Figure 1), or an infrastructure ‘pinch-point’ as identified by Mani et al. (2021), it could have the potential to be significantly higher.

Historic analogues: estimating losses from large-magnitude eruptions

In order to forecast potential losses from larger, ‘worst-case’ event scenarios in more populated regions, historic eruptions can be examined in more detail. Where economic losses for these events were not as accurately recorded as events in the last century, the hazards and their effects on populations, livestock and regional weather patterns are well-documented enough to be projected if they were to happen today. This type of predictive modelling is commonly used by (re)insurers to price products.

The 1707 Mount Fuji eruption released ~0.68 cubic kilometres of ash, reaching as far as Tokyo, and 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) is estimated to cause between 0.5-16cm of ash to fall over the city (Cabinet Office of Japan 2002). As well as airborne ash causing disruption to air traffic, such ashfall thickness would cause damage to electricity transmission lines, transport networks, machinery, contaminate water sources and potential 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 (100Tg) and fluorine over several months (Thordarson & Self 2003). Ensemble reanalysis shows subsequent winter temperature anomalies up to -3K below the mean in areas of the Northern Hemisphere (Zambri et al. 2019). 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 killing more than 60% of livestock from contaminated feed by the following year (Thordarson & Self 2003). A sulfur-rich effusive eruption today with similar gas hazards would likely cause widespread crop failures, livestock deaths and human respiratory issues. Estimated 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 in 2021 (Statistics Iceland 2023) global economic losses would likely total several billion. Subsequent climatic impacts like those modelled by Zambri et al. (2019) could result in additional losses, reaching trillions. Although the UK Government’s 2023 National Risk Register acknowledges risks to aviation from volcanic eruptions, with a ‘high impact, low probability’ VEI-7+ eruption having potential to cause major disruption to supply chains, international displacement, and hazardous weather, risks to human health, energy and financial security, agriculture and livestock are not discussed (HM Government 2023).

One of the largest recorded eruptions in history was Tambora 1815, however due to limited detailed records monetary losses are difficult to quantify. Pyroclastic density currents (PDCs) overwhelmed surrounding islands and caused tsunamis as high as 4m, released ~60 million tonnes (60Tg) of sulphur dioxide (SO₂) causing annual cooling over the next 3 years in the Tropics

and Northern Hemisphere by $\sim 0.4\text{--}0.8^{\circ}\text{C}$ 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 Laki, SO_2 release and subsequent cooling from a Tambora-like event would likely result in crop failures and food shortage across multiple countries, as well as reduced global average precipitation leading to droughts, and increased likelihood of extreme climatic 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 quantify costs of such an event, comparison of magnitudes from more modern eruptions can provide insight.

Scaling analogues to modern loss estimates, we can extrapolate from Mahalingam et al.'s 2018 economic study, investigating economic impacts of VEI-6 eruptions in Indonesia and US with estimated losses between \$2.5–7.6 trillion USD. Cassidy & Mani (2022) suppose a VEI-7 eruption with potentially larger climatic effects on food, water and energy security would exceed \$10 trillion, comparable to the COVID-19 pandemic. This is supported by Lloyd's Futureset tool, which estimates global economic losses between \$1.3–4.8 trillion for eruption scenarios 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 $\sim \$2$ billion per year (similar to values from recent decades from UN estimates; Figure 3). However, as UN data are based on smaller, regular eruptions during the study period, this would be additional to the \$7.6 billion per year quoted (\$9.6 billion total). Cassidy & Mani (2022) suggest investing in crisis preparedness and mitigation would be cheaper than reacting to a disaster (e.g. Woo et al. 2015), and call for increased attention and cooperation for research aimed at forecasting, preparedness and mitigation. Figures from recent eruption events 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. These findings support the case for further investment in research for volcanic hazard and loss modelling methods by insurers, providing volcanic hazard models and forecasting capabilities suitable to provide accurate scientific knowledge to underpin decision-making.

Cascading climate effects: volcanic forcing as a driver of insured loss

Volcanic emissions like ash, gases such as sulfur dioxide, and aerosols they produce can cause multi-year cooling for large magnitude eruptions. There is also evidence to suggest that radiative changes from aerosol dispersal may have wider implications on climate that could affect 'pre-existing' insurance payouts. Where past studies often examine volcanic hazards individually, these cascading volcano-climate impacts are examined to more accurately forecast potential loss amplification.

Alongside primary volcanic hazards, these wider climatic impacts are an overlooked threat the insurance industry should consider. Changes in intensity and location of extreme weather events from volcanic forcing are likely to have profound effects for industries such as agriculture (through storminess, frosts, flooding and drought, but also lack of photosynthesis from reduced solar radiation), water companies (decreased rainfall and drought affecting water security) and energy

companies (droughts leading to decreased biomass, less water for hydroelectricity, changes in wind patterns, and radiative reduction loss for solar).

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, finding that eruptions with significant aerosol forcing can impact 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.

8 of the 10 biggest insurance payouts of the 20th and 21st centuries resulted from Northern Hemisphere hurricanes (Aon 2024), suggesting a significant volcanic eruption 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 increased precipitation and intensity of Tropical Cyclone Cody.

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 risk of extreme droughts (Freychet et al. 2023). Similar results are also seen by Tejedor et al. (2021), with drier conditions over tropical Africa, central Asia and the Middle East, and wetter conditions over much of Oceania and the South American monsoon region for 1-2 years after tropical eruptions larger than Pinatubo 1991 across the 20th Century. Recent studies also show evidence that eruptions can increase 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).

Although for mid-sized eruptions these effects may be more localised, they can have cascading impacts on supply chains and financial markets globally, e.g. by blocking trade chokepoints (Bailey & Wellesley 2017). Although 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 incur losses. Volcano-related extreme weather events may also affect parametric insurance schemes meant to protect against effects of climate change (Ndlovu 2022), with compounding global impacts for years after an eruption that would be significant for reinsurance and their attribution to a cause. Mapping out potential cascading and systemic risks, escalating hazards, and modelling climate impacts in real time would give better 5 to 10-year forecasts for reinsurers. This would likely require an international body to govern the response, coordinate and distribute reliable data and models (Tupper & Bear-Crozier 2022).

When cascading climatic effects from eruption products are considered alongside primary hazards for volcano loss estimation, with evidence suggesting intensification of the biggest natural catastrophe loss drivers according to UN data (hurricanes) over a multi-year period, this further reinforces the idea that future eruption events may have significantly greater financial impact than previously considered. Losses have the potential to impact multiple sectors, with implications for both insurance and reinsurance products. This identifies a gap warranting further study, combining multi-hazard and loss modelling with cascading impact analysis to explore the full range of volcano-climate effects and resulting costs.

Regulatory approaches to volcanic risk

Given the serious impacts of volcanic disasters, governments and regulatory bodies must take steps to address volcanic risk within insurance and disaster management frameworks. Past reviews of financial solutions for volcanoes (e.g. Smolka & Käser 2015) don't detail how these fit into regulatory frameworks, and papers discussing regulation of catastrophe risk financing (e.g. Klein & Wang 2009) don't focus on specific natural disasters. Ensuring volcanic risk is considered by both governmental and private financing structures is a key consideration for future development.

Public insurance schemes and mandates represent an important approach for volcanically active countries. Iceland established a national Natural Catastrophe Insurance fund in 1975 (after a destructive eruption in Vestmannaeyjar, 1973) to provide compulsory coverage for 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 active 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 national schemes, regulatory oversight in insurance markets (such as Lloyd's) requires that insurers account for all material catastrophe perils, including volcanic, 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 (Chaplin & Adams 2024); 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 eruption generated total losses of up to £1 billion (\$2.8 billion USD today), described as a "surprise loss for the insurance industry" (Clay et al. 1999), 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), but this is still not commonplace for insurance markets in some exposed regions identified in this review. With increasing exposure and potential for cascading impacts, volcanic risk should be included in finance structures to avoid future surprise losses.

How can we better model volcanic hazards?

Research efforts have gradually advanced probabilistic volcanic hazard analysis and risk modelling methodologies. By the 2000s, volcanologists 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 PDC impacts. Industry-backed modelling initiatives have followed, though slowly. In the mid-2010s, at least one catastrophe modelling firm (Moody's/RMS) built an advanced probabilistic volcano risk model, but results remained unpublished and proprietary. More recently, Tennant et al. (2024) assessed tephra fall building damage using post-event UAV data and deep learning, going on to conduct probabilistic analysis using building exposure and vulnerability data to forecast losses (Tennant et al. 2026). Overall, volcanic risk modelling is still considered underdeveloped compared to models for perils like windstorm and earthquake.

Currently, there is little appetite by vendors (companies specialising in producing hazard and risk models for insurance and reinsurance broking) to model volcanic hazard and its losses. Deterministic models (fully relying on parameter values) provide retrospective or near real-time modelling. However, to forecast hazards and losses before an event occurs, as required by insurers and reinsurers, 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 by Guy Carpenter (Oramas-Dorta et al. 2021) and RMS (Miller 2007), appear to have either been abandoned or not widely adopted by the insurance industry. Reasons for this are likely due to relatively low losses from past eruptions compared to other natural catastrophes like earthquakes and wildfires (Figure 3), uncertainty from varying volcanic hazards and differing affected areas between volcanoes and even subsequent eruptions at the same location. The costs and computing power required for models incorporating these aspects makes 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 potential for volcanic hazards close to critical infrastructure or large magnitude eruptions to cause significant losses, such products should be revisited.

One example of an institution that currently has 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 impact assessment from earthquakes and volcanoes, with application in three countries around the Pacific Rim. This means GEM has capability for loss modelling of volcanic

hazards such as ashfall, PDC, lava and lahar, 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 PDCs (Patra et al. 2020), and Vrije Universiteit Brussel's 'Q-LavHA' plugin for lava flow (Mossoux et al. 2016), linking hazard footprints into OpenQuake to calculate loss values from GEM's exposure and vulnerability models. Although functional, these tools are from varying sources and differ in age, and this method doesn't account for individual volcano characteristics or ongoing unrest influencing risk of eruption. There is work still to be done providing more in-depth comprehensive modelling for these hazards.

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

Without subsequent processing and analysis, observation data is little use to insurers, and with the amount of data continuously provided by satellites the man-hours required would be unfeasible. This is where machine learning can be utilised, with deep learning frameworks called Convolutional Neural Networks (CNN) used to process data. The specific application of this framework for volcanic risk assessment is discussed by Biggs et al. (2022). This work uses automatically processed interferograms covering >1000 volcanoes globally from 2015-2020, identifying deformation signals that can indicate activity preceding eruption. This work helps improve machine learning algorithms and processing steps such as atmospheric correction, with the hope improved reliability can lead to design of real-time volcano monitoring and alert systems.

As data quality and processing methods improve, records of InSAR volcano deformation have been compiled and compared against where, when and what characteristics of deformation have resulted in historic eruptions within certain timeframes (Biggs et al. 2014, Jenkins et al. 2024). This comparison could be used to inform a probabilistic model of eruptions likely to happen over a given timeframe, and subsequently help form "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 be highly valuable to industries such as airlines.

Although work such as COMET's is useful for helping forecast if, when and where a volcano may erupt, this doesn't provide detail on hazard footprints themselves. Work by Biass et al. (2024) examines how assessment of large-scale population exposure to volcanic hazard usually relies on use of circular footprints, and this can under or overestimate hazard extent. This is where work 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 allow insurers to obtain important information from past eruptive scenarios, such as precursors, specific hazards, footprints and damage, as well as social impact and reactions from government and other institutions. By detailing historic eruption types and characteristics, combining with a probabilistic model using processed satellite data such as from COMET, this could mean 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 disparate, both warrant further investigation and funding in pursuit of a comprehensive, detailed and reliable framework for forecast-focussed insurance products.

Other initiatives aimed at modelling and reducing volcanic risks include ‘Myriad-EU’, a European Union Horizon 2020 research project assessing trade-offs and synergies between economic sectors, hazards and their scales for disaster risk reduction. Barcelona-based risk intelligence company Mitiga Solutions has 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, GEM, COMET, and the Willis Research Network bring together academic researchers, NGOs and institutions from across disciplines and geographies, and could help facilitate collation of databases and recourses necessary to shape products.

The now defunct ‘Global Volcano Model’ (GVM) brought together public and private institutions and organisations with the 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, 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, tsunamis and other natural hazards. Another such organisation is the 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 eruptions through advocacy and investment in preparedness, monitoring, skillsets and education.

Future research is needed to better characterize the frequency and impacts of extreme scenarios, 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), helping inform design of event caps or industry pools for ultra-catastrophic events.

There is also a gap in insurance coverage and product innovation. Many 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 eruption with more common risks.

Conclusion

With over 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 cannot 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 capability beyond basic analysis due to relatively low loss values compared to other natural hazards such as hurricanes and earthquakes. Economic losses from volcanoes have averaged \$7.6 billion per year from 1995-2015, but historical analogues of the largest eruptions in recorded history suggest a large, ‘fat-tailed’ event could cost tens of billions. In addition to ‘primary’ hazards from eruption products like PDCs and lava flows, ash and volcanic aerosols and their climatic effects have potential to disrupt supply chains, agriculture, transport networks and infrastructure, and influence weather patterns to change the location, timing or intensity of hurricanes, monsoons and droughts.

These potential impacts highlight that continued research and innovation is required, not only by academia but through a joined-up approach with (re)insurers to better incorporate volcanic hazards and their cascading effects into extreme event scenarios. Priority should be given to developing robust probabilistic models for different hazards and eruption scenarios, to better understand potential losses for insurance, and reduce impacts during future eruptions. This would serve to close a knowledge gap within risk modelling frameworks, and could help develop products to close the protection gap for vulnerable communities.

Severity Level	Scenario Description	Historic Analogue
Major	Ash cloud covers local area to 5cm depth , resulting in lengthy recovery.	Eyjafjallajökull, 2010 (VEI-4)
Severe	Ash cloud covers local area to a 1m depth , resulting in more complex recovery over potentially longer timeframe.	Pompeii, 79 CE (VEI-5)
Extreme	Caldera-creating explosion causes 2m deep ash coverage. Followed by volcanic winter , contributing to increased rainfall, flooding, and crop failures. Considerable recovery time, potential long-term impacts on global temperatures.	Mount Tambora, 1815 (VEI-7)

Table 1: Lloyd's Futureset scenarios for IAVCEI's 16 Decade Volcanoes (Avachinsky-Koryaksky, Colima, Etna, Galeras, Mauna Loa, Merapi, Nyiragongo, Rainier, Sakurajima, Santa María, Santorini, Taal, Teide, Ulawun, Unzen, Vesuvius) in proximity to 277 cities, at three severity levels. Source: Lloyd's & CCRS (2024).

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