The 1991 eruption of Mount Pinatubo in the Philippines, classified as VEI 6, cooled global climate by up to 0.7 °C for several years.

GEOSCIENCE

Volcanic threats to global society

Resilience plans for globally impacting cataclysmic eruptions are needed

By **Paolo Papale**[1] *and* **Warner Marzocchi**[2]

When Mount Tambora in the Lesser Sunda Islands, Indonesia, erupted in 1815, more than 100 km^3 of volcanic pyroclasts and ash were discharged into the stratosphere up to altitudes of over 40 km (*1*). The volcanic gases and ash dispersed over the Northern Hemisphere, causing what was called "the year without a summer" in Europe, with severe starvation, famine, mass migrations, and an estimated several tens of thousands of casualties. By comparison, the 2010 Eyjafjallajökull eruption in Iceland discharged only about 0.3 km^3—300 times less than Tambora—yet caused a week of air traffic shutdown and more than 100,000 flight cancellations over Northern and Central Europe, with an estimated economic loss of 3.3 billion euros (*2*). If an eruption of the scale of the Tambora eruption occurred today, its impacts would vastly exceed those of the 2010 Eyjafjallajökull eruption. Yet, global societies are essentially unprepared for such an event.

The 1815 Tambora eruption was large, but far from extreme. Its size is classified as 7 on the Volcanic Explosivity Index (VEI), which is a relative measure of the magnitude of volcanic eruptions. In the past 2 million years, there have been 27 so-called supereruptions (VEI 8, with an eruption volume >1000 km^3) (*3*), the most recent of which occurred at Taupo volcano, New Zealand, about 27,000 years ago. Four VEI 8 eruptions occurred in the past 100,000 years. The Toba eruption, which occurred in Indonesia 74,000 years ago, has been linked to a catastrophic decrease in global human population (*4*). The theory, however, is controversial (*5*), mostly because of uncertainty in the amount of sulfur released and the consequent extent of aerosol production in the atmosphere.

Smaller eruptions can have substantial impacts as well. The 1991 eruption of Mount Pinatubo in the Philippines (see the photo), classified as VEI 6, produced about 11 km^3 of tephra, injecting ~20 megatons of sulfur dioxide into the atmosphere and causing a years-long global cooling of up to 0.7°C. In historic times there has not been a supereruption, and humans therefore do not have direct knowledge of such extreme events. However, such an event would be likely to strongly affect global society. According to Sparks *et al.*, a supereruption could devastate an area the size of North America and cause weather deterioration, loss of crops, and severe disruption of food supplies, resulting in mass starvation and threatening the fabric of civilization (*6*). Such a situation would constitute an existential risk to humanity. A VEI 8 eruption, and to a large extent, a VEI 7 eruption, would shut down air traffic for weeks, months, or years over an area as large as the hemisphere, disrupting world trading and economies. There are no other known natural phenomena of endogenous origin (apart from flood basalts, which are orders of magnitude less frequent) that could disrupt our entire civilization so deeply and abruptly.

Although more than 800 million people on Earth live within 100 km of an active volcano and are directly exposed to detrimental short- to medium-range effects of volcanic eruptions (*7*), the occurrence of a supereruption in today's interconnected world extends that number to virtually the entire world population. Fortunately, most eruptions cause sizable impacts only within limited areas, although they can still be highly destructive given that many large cities are located in areas that are directly exposed to the effects of small- to medium-size eruptions.

The main means of volcanic risk mitigation today is the preventive evacuation of the population at risk, which requires identification and prioritization of the areas af-

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fected by dangerous volcanic phenomena, as well as early recognition of the signs of an impending eruption. Early recognition is aided by increasingly sophisticated volcano-monitoring networks, which measure ground displacements over wide frequency ranges, gas fluxes and chemistry, and, most recently, variations in local gravitational acceleration and the underground electromagnetic field (*8*). Experience in developing countries shows that even a basic monitoring system can be effective in saving lives in many situations. However, in urbanized, industrialized areas, it can be difficult to ensure sufficient time for preparing the city for mass evacuation while minimizing the risk of a false alarm, which may carry high social and economic costs and could undermine trust in scientists and civil protection authorities (*9*).

Despite the enormous progress in volcano monitoring, there is no generally accepted practice for forecasting of the eruption size. The extreme nonlinear dynamics that control volcanic processes may prevent a deterministic assessment of their size, and therefore of their impacts, before the eruption (*10*). Therefore, present-day hazard and risk maps and associated evacuation plans can only be based on statistics from past events. The common practice is to refer to the past history of the volcano under inspection, sometimes complemented with observations and data from volcanoes considered to be analogous (*11*).

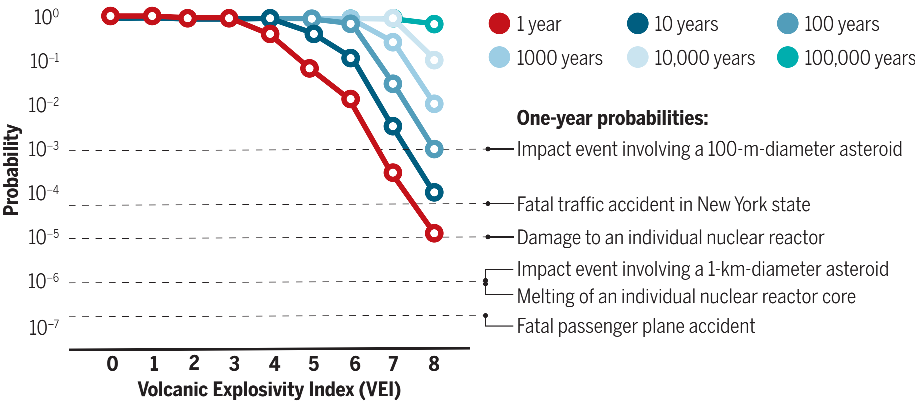
The above risk-mitigation strategies lose their significance when considering cataclysmic volcanic eruptions, with global impacts going well beyond direct exposure to the volcanic phenomena. Knowledge of the probability of occurrence of a globally devastating volcanic eruption somewhere in the world (see the figure) allows a quantitative evaluation of the volcanic hazard from such large-scale phenomena. On the planetary scale, the temporal occurrence of volcanic eruptions follows a Poisson distribution (*10*), and their probability therefore depends only on the length of the forecasting time window. The time that has passed since the last VEI 7 or VEI 8 eruption does not affect when the next one is going to happen. Globally impacting, cataclysmic volcanic eruptions punctuate Earth's history, displaced in time in an apparent disordered way that in fact reflects the exponential distribution of their return times, this being a fundamental characteristic of Poisson-distributed events.

Comparison with the probabilities associated with other adverse events helps to provide context. For example, since the mid-1950s, about 450 nuclear reactors have been built around the world (*12*), with the provision that the probability for each individual reactor to experience a nuclear accident involving core melting is lower than that of a VEI 8 eruption on the planet (see the figure). There is no model for evaluating the risk associated with a volcanic supereruption—given by a combination of the probability of occurrence (the hazard; see the figure) and the value expected to be lost. But it is clear that a VEI 8 eruption is incommensurably more devastating than an individual nuclear reactor meltdown.

Although VEI 7 eruptions are smaller than VEI 8 eruptions, they can destabilize national economies and even jeopardize peace between nations. Their effects on global air traffic, global communication systems, and climate are expected to be extensive.

Probabilities of volcanic events

The probability of at least one eruption of a given VEI size on Earth is shown over different time intervals from 1 to 100,000 years. The 1-year probabilities of these events are compared to those for other threats. See supplementary materials for details and sources.



Newhall *et al.* argue that a VEI 7 eruption in Indonesia in the 13th century largely contributed to, and likely was one major cause of, the cold conditions during the Little Ice Age (*13*). Their estimate of the probability of VEI 7 eruptions is higher than those in the figure, mostly because of the addition of a number of VEI 6 eruptions assumed to have been underestimated according to their expert judgment. In the more conservative estimates shown in the figure, VEI 7 eruptions are nearly 30 times more probable than VEI 8 eruptions. Over the next 100 years, the probability of observing a cataclysmic VEI 8 eruption is 0.12%, growing to as much as 3.6% for a highly disruptive, globally impacting VEI 7 eruption. The above considerations imply that the likelihood of a cataclysmic eruption with the potential to severely affect or even disrupt human civilization is far from remote. Governments are investing considerable amounts in developing plans to defend Earth from the impact of a kilometer-size asteroid (*14*), an event with a probability that is 10 to a 100 times smaller than that of a global volcanic catastrophe (see the figure). Humanity should not simply wait for a next cataclysmic Toba or Yellowstone-size eruption or a relatively smaller, much more probable, but still globally disrupting Tambora-size eruption. Rather, there is a need to develop a strategy for enhancing human resilience and for safeguarding the critical nodes and elements necessary to defend the level of progress and civilization that humans have achieved. ■

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SUPPLEMENTARY MATERIALS

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