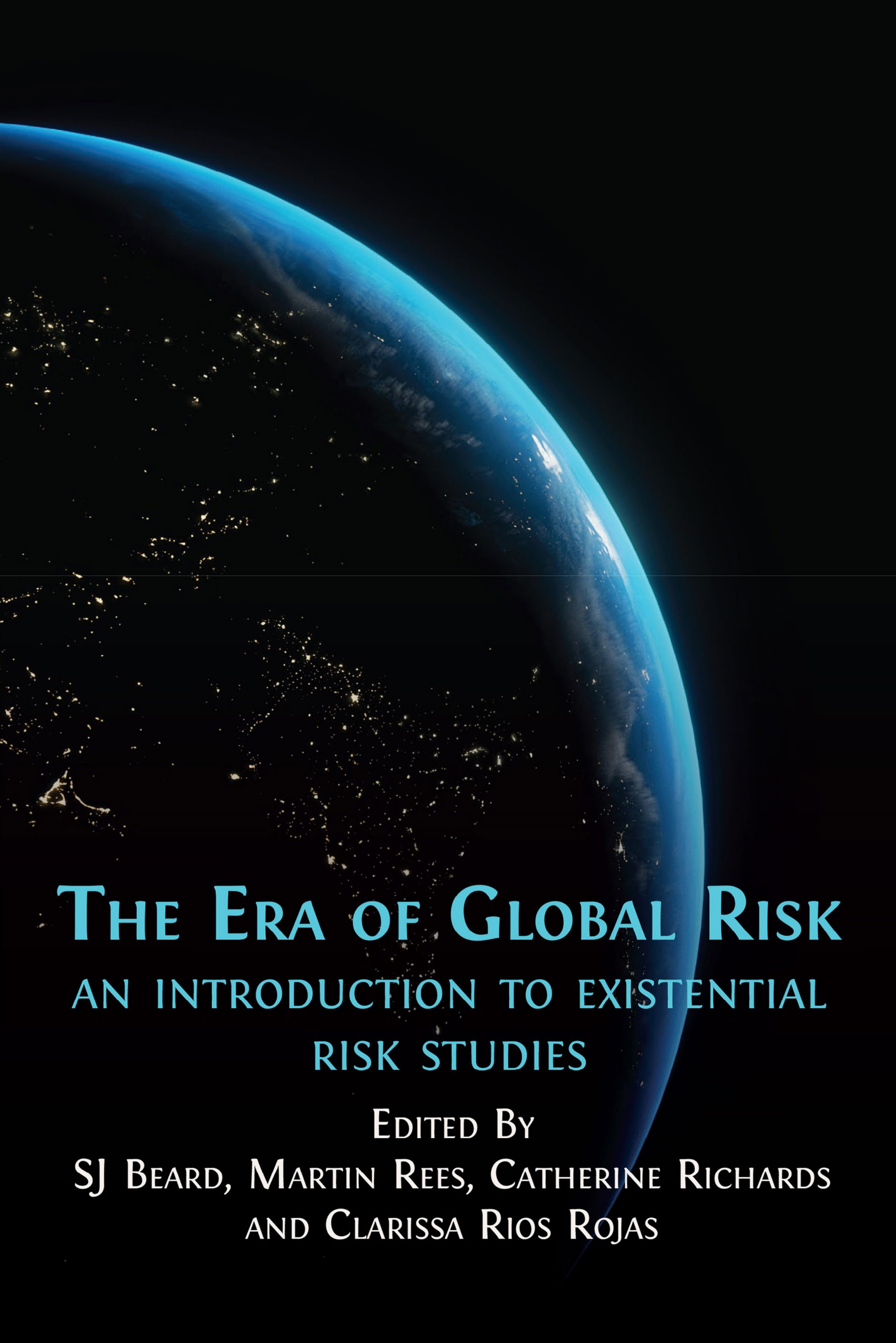

The Era of Global Risk

An Introduction to Existential Risk Studies

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6. Natural Global Catastrophic Risks

Lara Mani, Doug Erwin, and Lindley Johnson

Civilization exists by geological consent, subject to change without notice.
Will Durant, historian (1885–1981)

Humanity has lived with the threat of certain global catastrophic risks throughout history, such as large-magnitude volcanic eruptions and Near-Earth Object (NEO) impacts. But the risks of such events have grown with the increasing complexity of human societies. The probabilities of natural global catastrophes are not negligible, although these risks are often underestimated. Moreover, the societal and economic impacts of some of these events are potentially vast. So, to what extent is humanity truly vulnerable to natural catastrophic risks, and what does this risk landscape look like? Here, we explore the state of current thinking around extreme natural risks and explore the dichotomies often neglected on the peripheries of these discussions.

The past as a lens for the future

The geological record is the greatest tool that humanity possesses in informing discussions of our exposure and vulnerabilities to high-impact, low-probability natural risks. By studying the stratigraphy of our Earth's past, geologists have built a picture of the potential futures that may await us. French natural historian Georges Cuvier first identified catastrophes in the fossil record of the Paris Basin in the early 19th century, and progress has waxed and waned since then. In 1982, using the fossil record of marine animals (mostly invertebrates), Sepkoski and Raup presented evidence

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for five mass extinction events over the past 500 million years, where a mass extinction is a substantial increase in lineage extinction across multiple clades in a relatively short amount of time.[1] The vagueness of this definition is intentional, to capture a variety of possible events.

Over the past several decades palaeontologists, stratigraphers, geochemists, and others have conducted detailed studies of specific extinction horizons, as well as compiled global, synoptic databases of past biodiversity. This work has greatly improved our resolution of the fossil record and clarified the number, extent, and rate of past biodiversity crises.

Before detailing the results and implications of these studies, some reflection on the nature of the data is warranted. The primary source of information on past biodiversity crises is the fossil record of durably skeletonised, geographically widespread and abundant marine invertebrates, as well as similar microfossils such as foraminifera and radiolarians. It is the record of these groups that is preserved with sufficient fidelity to permit regional and global correlation of the sedimentary geological record. These fossils are also preserved with sufficient continuity that we can, with appropriate statistical analysis, have reasonable confidence in the accuracy of the resulting patterns. Many marine organisms are difficult to preserve as fossils, either because they lack durable skeletons or for other reasons, and these are largely absent from such synoptic compilations. Palaeontologists have compiled records of terrestrial plants, insects, and vertebrates, but the quality of their fossil records generally precludes using them to *identify* past biotic crises, except in relatively young deposits. Rather, palaeontologists tend to identify crisis intervals in the marine record, and then seek correlative terrestrial records to examine the potential impact on terrestrial ecosystems.

Today, palaeontologists generally identify three great mass extinctions with rapid drops in biodiversity across many different taxa: in the late Ordovician (444 Ma), end-Permian (251 Ma), and end-Cretaceous (66 Ma), and a possible fourth at the end-Triassic (199 Ma). In addition, there was a prolonged decrease in diversity through the Late Devonian, but this was more drawn out than other episodes. As the resolution of the data has improved, a series of smaller events has also been identified, with perhaps a total of at least 18 biotic crises events affecting marine taxa—with some affecting both marine and terrestrial taxa.[2] There have almost certainly been additional crises that primarily affected poorly preserved taxa, either marine or terrestrial, but which are missing from the synoptic compilations used in these studies. Animal fossils only appeared about 550 million years ago, so we lack a sufficiently high-resolution fossil record before that time to reveal older biodiversity crises. Species extinctions have been ubiquitous through the history of plant and animal life, and the majority of these have not been concentrated in these discrete episodes. Nonetheless, biodiversity crises, often tied to environmental perturbations, are a natural process. But what drives biotic crises and what governs when a crisis tilts to become a mass extinction event?

The major mass extinctions share several common features: First, high-resolution radiometric dating has revealed that most were relatively rapid, occurring in just a few tens of thousands of years (or less), rather than over hundreds of thousands or millions of years.[3] This suggests that whatever the cause or causes that trigger a mass extinction, once collapse is triggered it is very rapid. To a first approximation, every event that has been studied in detail happened more rapidly than we can resolve with current techniques. Second, all were global, and all but the end-Ordovician impacted both marine and terrestrial organisms (there was little life on land at that time). Third, these extinctions were selective, more heavily impacting some clades rather than others—brachiopods and ammonoids, respectively, at the end-Permian and end-Cretaceous, for example. Fourth, although palaeontologists have traditionally focused attention on the loss of diversity, most of these were profound ecological disruptions as well, rending food webs.[4] The exception to this generality was the end-Ordovician event which, despite being the second largest mass extinction, had little ecological impact. Finally, rapid climatic change (either cooling or warming) has been implicated in each event, as well as pervasive marine anoxia. The net effect of all these crises has been the progressive loss of clades unable to survive such events or to recover after such widespread losses of diversity.

Dozens of possible causes have been suggested for mass extinctions, but proximal causes—those directly responsible for the disappearance of particular species—must be distinguished from mechanisms that generate the proximal causes. Most studies of the end-Cretaceous mass extinction have concluded that the impact of an extra-terrestrial object in the Yucatan peninsula of Mexico was the cause of the extinction,[5] but species largely disappeared as a result of the environmental effects of the impact, including climate change. Massive volcanism in India roughly coincides with the extinction event, and some continue to argue that it was involved, although most studies suggest that the peak of the volcanic eruption pre-dates the impact and extinction. Massive volcanism has also been implicated for the end-Permian[6] and end-Triassic events,[7] while a rapid glaciation was probably the cause of the end-Ordovician extinction.[8] The end-Permian mass extinction has long been tied to the eruption of the massive Siberian flood basalts, the most extensive continental flood basalt province in the past 500 million years. Beyond the Siberian volcanism, subduction-related massive volcanism spread copper and mercury across wide areas of south China at the Permo-Triassic boundary.[9] These volcanic events caused rapid cooling followed by a 4–6°C temperature increase, oceanic anoxia, and acid rain from sulphate aerosols.

One of the most controversial issues in extinction research is the impact of mass extinctions and other crises on pre-existing evolutionary trends. In particular, do clades that acquire extinction-resistance prior to a crisis have better survival rates during mass extinctions? Numerous studies of this question have been conducted over the past several decades, arriving at sometimes contradictory results.[10] Overall, however, much of this work suggests that the acquisition of resilience often enhances survival during biotic crises. There may be an important lesson here for human societies. Politicians and voters often fail to focus on long-term concerns, including natural catastrophic risks of the sort described in this chapter. If, however, resilience to crises on shorter time scales—such as hurricanes, volcanic eruptions, or massive wildfires—might also enhance the survivability to far rarer events, this suggests that pursuing a properly constructed resilience strategy may have substantial societal benefits.

The geological record presents dire warnings for humanity if extreme natural risks are left unmitigated. Our world could experience a new biotic crisis due to rapid onset climate change, with accelerated species extinction already taking place. And, although our surveillance may provide us with ample warning of a potential large NEO impact, we remain exposed to such a threat with no means of mitigation and prevention available. However, the geological record can only go so far as informing us of what extreme natural hazard events have looked like in the past. To understand the impact of such an event in the future, we must consider the present-day landscape for natural global catastrophic risks and how vulnerability is a key component in understanding the systemic nature of risk.

The changing landscape of extreme natural threats

We are now entering a new geological epoch—the *Anthropocene*—characterised by humanity as the biggest driver of change to our planet's climates and ecosystems. Anthropogenically driven climate change is accelerating and strengthening some of our Earth's natural processes. Today we face an increasingly complex risk landscape where hazards can be interconnected, where one natural hazard event can increase the probability and/or severity of another hazard. For example, extreme weather events (such as flooding or drought) can result in crop failures and damage to critical infrastructures such as water and sanitation, resulting in disease outbreaks.[11] Certainly, we are now experiencing more disasters than ever before, with over four billion people affected by disasters over the past 20 years, up 1.2 billion from the 20 years prior.[12] Some evidence suggests that despite this increase in disasters, our resilience to smaller-scale disasters is also increasing, with the average annual loss of life due to disasters representing around 0.1% of global deaths.[13] However, shock events—such as the 2004 Indian Ocean tsunami, or the 2010 Haiti earthquake—can significantly elevate the global death toll, and humanity remains vulnerable to low-probability, high-impact risks.

Large-magnitude volcanic eruptions and asteroid and comet impacts represent natural hazards that may lead to either extinction of humanity or to grave consequences affecting humanity's continued flourishing. Here, we review this hazards in the light of improved surveillance and new research into the threats they pose.

Large-magnitude volcanic eruptions

The critical risk to humanity posed by volcanic eruptions is centred on large-magnitude 8+ eruptions, or so–called super-eruptions. These are explosive eruptions that eject over 1000 km^3 of material.[14] Certainly, an eruption of this scale would have severe consequences for humanity, with ash and gas propelled into the upper atmosphere, where they would interact with our climatic systems, reducing global surface temperatures and potentially devastating global food production. This climatic feedback mechanism is typified by the 1815 magnitude 7 Tambora eruption, which released 30 megatons of sulphur, resulting in short-term climate anomalies (primarily in the northern hemisphere).[15] During the summer of 1816, Europe is thought to have experienced temperatures of 1–2°C lower than normal as a result of the eruption, and summer temperatures remained anomalously cooler in 1817 and 1818 respectively.[16, 17]

The climatic cooling mechanisms for volcanic eruptions are often compared to that of the nuclear winter mechanism, by which the black soot particles from nuclear warfare would block the sun's energy, resulting in a global cooling effect. For volcanic eruptions, it is rather the sulphur gas released during the eruption that mixes with water in the atmosphere, creating droplets of sulphuric acid which reflect sunlight back into space and absorb heat from the Earth.[18] The resulting effect is a cooling of the lower atmosphere and a warming of the upper atmosphere.[19] This mechanism is important to understand, because the magnitude of an eruption does not necessarily correlate to the quantity of sulphate released. In fact, lower magnitude eruptions of magnitudes 6 and 7 are capable of releasing significant quantities of sulphate gas to instigate this climate cooling effect. One such example is the 1257 magnitude 7 eruption of Mt Rinjani, Indonesia. Detected by a strong sulphate signal in ice core records, this eruption is thought to have triggered the onset of the Little Ice Age, resulting in famine across Europe and the deaths of over 10,000 people in London alone.[20] Abrupt climate cooling events have now been linked to several volcanic eruptions, including the 1991 eruption of Mt Pinatubo, the 1257 eruption of Mt Rinjani, and the 1883 eruption of Krakatau. Using new ice core records, a recent study identified, during the Holocene (the past 10,000 years) over 160 explosive eruptions releasing quantities of sulphur greater than or equal to the 1815 Tambora eruption.[21]

Since the 1815 Tambora eruption, our natural global systems and processes have undergone significant changes as a result of climate change. One such process of significance to volcanic eruptions is the Brewer-Dobson global atmospheric circulation pattern, by which warm tropospheric air rises to the upper atmosphere and sinks at the poles, which is now accelerating due to greenhouse gas emissions.[22] Volcanic aerosol injection is also known to accelerate the Brewer-Dobson circulation, and the combined effect of anthropogenically driven climate change and volcanic eruptions can substantially increase the rate at which volcanic ash and gas are pushed towards the Polar Regions, increasing the rate of global surface cooling.[23] Additionally, the increased sulphate aerosol in the atmosphere in the aftermath of a major volcanic eruption can result in a reduction of global mean precipitation.[24] By these effects, models run by Aubry et al. predict that global surface cooling for eruptions in the tropics could lead to 15% more global surface cooling than seen in 1815, and as much as 60% more when ocean feedbacks are also factored in.[25] By this calculation, a future eruption the size of the 1815 Tambora eruption in the tropic regions could cause up to 3.2°C global surface cooling.

The implications of such a global surface cooling event could be catastrophic for global food production, devastating food production regions. Simulation models of the Toba eruption, which occurred ~74,000 years ago,[26] suggest that if a similar event were to occur today, few regions of the world (with the exceptions of southern Africa and India) would remain unaffected by global surface cooling and a reduction in precipitation. A loss of any of the global food production regions could have catastrophic consequences for the world population, resulting in widespread famine, increased fuel and food prices, disease outbreaks, and regional conflicts. Ord (2020) suggests that billions of people could starve in this scenario and, if civilisations are unable to recover, it could result in an existential catastrophe.

Not only are the resulting consequences of volcanic eruptions becoming more extreme due to the expansion of human civilisation, the frequency of eruptions may be increasing. The melting of snow and ice sheets on volcanic centres, higher sea levels, and increased rainfall in some regions are thought to change the stresses in volcanic systems, removing the overlying weight burdens. As the pressures change within the system, this can encourage fresh magma to ascend to the surface.[27] With climate change now an amplifier of volcanic hazard, evidence is building to suggest that lower magnitude eruptions (VEI <8) should be considered within our probabilistic forecasts for extreme volcanic risk scenarios. From the geological record, the recurrence interval for VEI 7 eruptions is estimated between 1 and 2 eruptions per 1,000 years and new ice core record data corroborates this, suggesting the recurrence interval could be around 1.16 eruptions per 1000 years. By this logic, the recurrence interval could be as short as 625 years for a magnitude 7 eruption—or one in six this century.[28]

Fields such as volcanology are in their naissance, and volcanologists still have a long way to go before being able to answer some of the most fundamental questions about volcanoes. Many of the forecasts of probabilities for such risks fail to acknowledge the outstanding uncertainties in the geological record or to consider the advancements in our surveillance techniques, leading to an underestimation of the risks. For the field of volcanology, lessons can be learnt from the field of planetary defence about the importance of increased surveillance and monitoring for constraining the threats posed by Near-Earth Objects.

Near-Earth objects—Asteroids and comets

To date, there are more than 190 confirmed impact structures spanning Earth's recent geologic history known around the world. Examples include the Manicouagan Crater in Canada: at 85 km wide, it is thought to have resulted from a ~5 km impactor some 214 million years ago, and the Lonar impact crater in India is thought to have occurred around 570,000 years ago. The most significant damage recorded from an asteroid impact in recent history is from 1908 Tunguska, Russia, where a 40-metre object exploded before surface impact, causing an air blast that devastated over 2,000 km^2 of forest in Siberia, and is believed to have had measurable effects on the global climate in the subsequent year. However, impact events remain relatively rare, with regional scale devastation events (caused by object impacts over 140 metres) estimated to occur every 20,000 years (Table 1). Despite the low probabilities associated with these events, the threat of impact remains present, and impact events could happen at any time where, unlike other natural hazard events, the location of impacts is not confined to specific regions.

Table 1. The potential expected impacts and estimated recurrence intervals for a range of asteroid impacts sizes. The range shaded in grey identifies the diameter of impactors typical considered to be capable of global catastrophe (adapted from NASA[29]).

Diameter of impacting asteroid (metres)	Type of impact	Average time between impacts (years)
5	Bolide	1
10	Super bolide	10
25	Major airburst	100
50	Local scale devastation	1,000
140	Regional scale devastation	20,000
300	Continent scale devastation	70,000
600	Below global catastrophe threshold	200,000
1,000	Possible global catastrophe	700,000
5,000	Above global catastrophe threshold	30 million
10,000	Mass extinction	100 million

Near-Earth Objects (NEOs) are asteroids and comets that come within 1.3 astronomical units (the mean distance between Earth and the sun) of the sun, bringing them within 50 million kilometres of Earth's orbit.[30] A subset of NEOs can be described as Potentially Hazardous Objects (PHOs), meaning their orbits bring them within eight million kilometres of Earth over time, and they are of sizes capable of causing devastating regional damage should they impact (>140 metres in size). In 2010, with over 90% of all NEO objects greater than 1,000 metres in size already discovered,[31] the National Aeronautics and Space Administration (NASA) began searching for 90% of NEOs larger than 140 metres in size.[32] NASA identifies over 2,500 Near-Earth asteroids a year of all sizes, with an average of 500 being larger than 140 metres in size, using a system of both ground-based telescopes (e.g. Catalina Sky Survey, ATLAS, and Pan-STARRS) and the NEOWISE space-based telescope. With a population estimated at over 25,000 objects larger than 140 metres in size, at NASA's current discovery rate this task is expected to take over 30 years to complete. To speed up the identification process, in 2026 NASA plans to launch a new NEO detection and tracking space telescope called 'NEO

Surveyor', which will detect in the infrared spectrum and is designed to identify over 90% of the still unknown hazardous NEO population within 10 years of operation.

In 2021 alone, there were over 145 close approaches within the distance of the moon's orbit by NEOs,[33] most of which measured just a few metres to a few tens of metres in size. In this size range, any object on a collision course with Earth would likely disintegrate in our atmosphere before impact. However, one asteroid in 2021 was as much as 90 metres in size, substantially larger than the one causing the Tunguska impact. A few even larger objects make close approaches every few years, such as the '2019 OK' asteroid which measured ~100 metres wide and passed within approximately 70,000 km of Earth in July 2019. Alarmingly, this object was not detected until just a day before its close approach, despite it having been included in surveillance imagery by both Pan-STARRS and ATLAS. The object's slow rate of apparent movement relative to the background of stars meant that it was not identified as a closer moving object, and therefore remained undetected.[34] The '2019 OK' event somewhat echoed the 2013 Chelyabinsk impact event, which also went undetected until its actual impact with Earth on 15 February 2019 over a densely populated region of Russia. In the case of Chelyabinsk, the lack of prior detection was due to its approach in the daytime sky. The object's approach from the direction of the sun meant that an already small and faint object would have been very difficult to detect, even if our telescopes had been directed at it.[35] The resulting impact caused widespread building damage in the region of over 7,000 properties, and injury to an estimated 1,400 people, mainly due to shattered glass as a result of the shockwave it caused. Both the '2019 OK' close approach and the Chelyabinsk impact event serve as stark reminders of humanity's continued vulnerability to NEO impacts, and of the blind spots and limitations of our current surveillance capabilities.

Not all NEO impact events may have catastrophic consequences for humanity—the end-Cretaceous impact event did not kill all living species on Earth, despite the object's size being well into the realms of causing global disaster, but rather led to the demise of the dominant species so that the diminutive mammals of the era could begin their ascent on the planet. Objects over 1 km in size are considered to pose the most threat to humanity's continued flourishing, and the recurrence interval for these events is around 700,000 years (Table 1), over a thousand times less probable than a magnitude 7 eruption.[36] More likely are the impacts from objects between 100–300 metres, which could still cause substantial regional devastation. If an impact of this size were to occur in food-producing regions, for example, the cascading consequences could be comparable to a volcanic global cooling event, described above.

Both the examples of high-impact volcanic risks and the threat of an NEO impact demonstrate how such events could result in globally felt consequences, amplified by the impacts to global food production and the stresses this could exert on human civilisation. This highlights the need to increasingly consider the systemic nature of natural risks, and particularly the aspects of vulnerability as amplifiers of global risks.

The systemic nature of natural risks

Borrowing from the disaster risk literature, risk is often seen as a combination of components of hazard and vulnerability (and exposure), where the relationship can be defined as:

Hazard x Vulnerability (x Exposure) = Risk

In a crude sense, this risk equation is a simple way to consider the key components of risk, and this remains relevant for the consideration of high-impact low-probability natural risks, such as asteroid impacts or high-magnitude volcanic eruptions. However, this approach often fails to encapsulate the dichotomies around the components of hazard and vulnerability, or consider how humanity's capacity to cope with hazards (or vulnerability) can alter the severity of the risks. Some existential risk authors, such as Liu et al.[37] and Avin et al.[38] have made steps towards adopting 'systemic risk' thinking rather than siloed 'hazard' thinking, and here we continue to build upon this progress by considering the mechanisms by which natural hazards could be amplified to natural global catastrophes.

Cascading to catastrophe

Our world has become interconnected and complex, with our societies relying on a myriad of systems and networks to sustain them and support their continued development—known as global critical systems (GCS).[39] These systems (such as communications networks, transportation routes, and trade links) are vital arteries in our modern world. Global critical systems and infrastructures, such as maritime shipping routes, submarine cables, global position navigation and timing (PNT) systems, aerial networks, ports, fuel pipelines, and power plants (amongst others) are critical to the transport of goods, services, and commodities around the world. However, these systems are often fragile, with little to no resilience built in to deal with shocks and interruptions. Any disruptions to these systems can instigate a cascade of impacts across interdependent systems.[40] For example, in March 2020, the *Ever Given* container ship blocked the Suez Canal—a busy maritime trade passage—for six days, with ships stuck either side of the passage for weeks to months in the aftermath. The resulting disruption saw global container ports overwhelmed and significant delays to global supply chains, costing an estimated $6-10 billion a week to global trade. Within the field of Disaster Risk Studies, this type of chain reaction of impacts is described as cascading risk.[41]

The extent to which a cascade of system failures escalates to global catastrophe is a component of what systems are affected and how well we are able to cope with them. Response to a natural hazard event can erode our ability to cope with other shocks and hazards, and can even amplify the impacts of subsequent impacts in other related and interconnected systems.[42] The COVID-19 pandemic has revealed the nature of our interconnected systems, with pressures on the health sector resulting in knock-out effects on the economic and political sectors. Other examples of this mechanism include Syria, where severe drought conditions experienced between 2007 and 2010 devastated the food production regions, resulting in unemployment and food insecurity for over one million people, contributing to conflict in the region.[43]

The links between natural hazards and human civilisation are well documented, with volcanic activity linked to the collapse of the Maya, Romans, and Minoans, amongst others,[44] and even changes in Earth's magnetic field linked to societal declines. However, in many of these examples, volcanic activity was only considered a contributing factor, rather than the outright cause. Additional risk drivers—such as droughts or other natural hazards, conflict, and food scarcity—were often associated with these collapse events, where a compounding of shocks and a cascade of failures amplified the impacts. In our modern and connected world, these same processes could see natural hazard events catapult to global catastrophes.

A recent study by Mani et al. looked at this cascade mechanism in relation to active volcanism in proximity to regions where a high convergence of GCSs were observed, representing regions of heightened societal vulnerability.[45] They present seven global 'pinch points' where the interaction between volcanic hazards and multiple GCSs at these convergence zone could result in a cascade of system failures, leading to global impacts. Interestingly, the study expresses that lower-magnitude eruptions (magnitude 3+) could be capable of instigating such a cascade of impacts, though they are typically considered outside the realm of disaster causation. Liu et al. (2018) express this relationship as an imbalance of the risk equation, moving away from consideration of just 'existential hazards' towards 'existential vulnerabilities'.[46] If a hazard event or sequence of hazard events were to occur in proximity to these regions of heightened societal vulnerability, such as pinch point regions, the consequences could be catastrophic for humanity, highlighting the importance of consideration for the systemic nature of risk in the practice of global catastrophic risk research.

The systemic nature of risk is important to consider for other extreme natural hazards such as stellar explosions, coronal mass ejections, and the reversal of Earth's magnetic field, amongst others. Not all of these risks may pose a direct threat of human extinction as we currently understand it, but the risks they pose to their systems and infrastructures that sustain our societies could constitute a global catastrophic risk and even push us towards collapse. For example, if an event similar to the 1859 Carrington Event (a geomagnetic storm caused by a coronal mass ejection)[47, 48] were to happen in our modern and interconnected world, the impacts could be grave if we are not prepared. Electrical surges in power grids could cause them to shut down with consequences to our water, sanitation, food and energy supplies, and health systems, and satellites and communication networks could be damaged, with disruption to global transport and trade leading to severe impacts on our global economic, social, and political systems.[49] For events like geomagnetic storms and coronal mass ejection events, they can be detected in advance of their arrival on Earth, meaning we could have the time to prepare and respond so we can reduce the potential impacts, such as shutting down electricity grids temporarily to avoid disruption. However, without adequate preparation and resilience measures put in place in advance, and considerations for the systemic nature of such risks, we remain vulnerable to the cascading consequences of such events.[50]

Mitigating and preventing natural risks

Natural catastrophic risks, such as those described in this chapter, have long posed a threat to the continued existence of humanity. By increasing the exposure of our societal vulnerabilities to regional natural hazard events, we have manufactured a new landscape for global catastrophic risks. By improving our understanding of the drivers that proliferate a hazard event towards a global catastrophe, we can consider the best methods and strategies to adopt in order to strengthen our resilience to the risks. So, what can we do to reduce the risk posed by natural catastrophic risks? One field that is making strides in this realm is planetary defence.

Lessons from planetary defence

After the 2013 Chelyabinsk impact event, global governments were motivated to increase our resilience to NEO impact threats. In 2018, guidance was handed down to NASA from the White House that tasked them with developing preparedness and mitigation strategies for an Earth-bound NEO. The guidance sets a clear focus for improving our understanding of NEO threats: to increase surveillance capabilities and to establish robust response and mitigation strategies.[51] With a modest budget of around $150 million a year (expected to rise to $200 million in 2022), the Planetary Defense Coordination Office (PDCO) at NASA works towards these goals.[52] So, what can be done if we detect an object on an Earth-bound trajectory?

Depending on the timescale that we may be afforded once an Earth-bound object is detected, different technologies can potentially be deployed to deflect or disrupt it. Many of the current methods and techniques employ the sample principle—change the orbital speed of the asteroid several years before potential interception with Earth, and the object's trajectory will no longer synchronise. Several methods and techniques are currently considered for deflection and disruption, including gravity tractor, nuclear detonation, and kinetic impactor. The gravity tractor technique simply uses the forces of gravity to either push or pull the object off its current trajectory. Where we are afforded time (in the form of decades), a spacecraft can be launched to meet the asteroid, stationing itself in proximity. The close presence of the spacecraft then generates a gravitational attraction between the two bodies, slowly tugging at the asteroid and pulling it from its orbital track, out of the path of collision with Earth.[53] Nuclear detonation using a Nuclear Explosive Device (NED) could be employed when we are afforded less time (a decade or less). By detonating an NED in proximity to an object, this can irradiate the surface of an asteroid, super-heating the release of material from the surface, causing a reaction force of the asteroid in the opposite direction. However, nuclear detonation techniques come with high levels of uncertainty, and the use of nuclear devices in space (and the employment of this method) would involve the careful navigation of the Outer Space Treaty and global geopolitics.

As part of the international Asteroid Impact and Deflection and Assessment (AIDA) collaboration, in November 2021 the first of two missions was launched to demonstrate the kinetic impact technique. NASA's Double Asteroid Redirection Test (DART) mission launched towards the binary asteroid Didymos, with the aim of crashing the probe directly into the asteroid's small moon, Dimorphos. It was designed so that the collision event would change the orbital speed of Dimorphos and thus, test the plausibility of using the kinetic impactor technique for future Earth-bound NEO threats. Early indications suggest the mission was successful, with the impact shortening the orbital time of Dimorphos around Didymos by 32 minutes. A second mission—the HERA mission, led by the European Space Agency (ESA)—will launch in 2024, headed for the Didymos/Dimorphos asteroid pair. The HERA mission is designed to measure the effectiveness of the kinetic impactor by DART, by better characterising the asteroid, the effects of the impact of DART, and more precisely measuring the body's mass and internal structure. If both DART and HERA prove successful, we will move a step closer in our capabilities for asteroid deflection.

Although these are promising steps towards developing our capabilities for mitigation of an NEO threat, we are still years away from being able to utilise kinetic impactor technologies for a real-time event. With this in mind, the planetary defence community has worked extensively, through international cooperation, to establish potential disaster response strategies for an impending NEO impact. The development of the National Near-Earth Object Preparedness Strategy and Action Plan in 2018 called for a strengthening of the US response to an asteroid or comet impact.[54] To this end, the field has extensively employed the use of scenario-based simulation exercises to stress-test the global response to an asteroid threat. A similar exercise is adopted for the wider planetary defence community at the bi-annual International Academy of Astronautics (IAA) Planetary Defense Conference.[55] The exercises include considerations of the global consequences to our climatic systems and for civil protection strategies, and engage a range of experts from across disciplines to provide a holistic approach to considering the risk posed by hypothetical impact scenarios.[56] These interactive exercises provide the opportunity to assess the global response mechanisms for such a risk, assign duty bearers, and identify weaknesses in capabilities and capacities to cope. The use of scenario exercises provides us with useful thought experiments for mitigation and prevention of natural catastrophic risks, with application across numerous other global catastrophic risk domains, such as biosecurity and nuclear war (some of which are already using simulation, e.g. Johns Hopkins Center for Health Security).

The strength of the planetary defence community is the strong push for international coordination and the adoption of interdisciplinary approaches to mitigating the risks, presenting a model for other catastrophic natural risks. The planetary defence community demonstrates the importance of taking actions now that may better prepare us for future natural catastrophic events.

Mitigating volcanic eruptions

Despite the higher probability of volcanic eruptions (over NEO impacts) having catastrophic consequences on humanity over the next century, little work is currently being done to consider potential mitigation and prevention methods. Often, volcanic eruptions are deprioritised in comparison to other natural hazards, largely because it is thought that little can be done to mitigate them.[57] However, the recent NASA DART mission, combined with the eruption of the Hunga Tonga-Hunga Ha'apai eruption in the South Pacific in January 2021, has accelerated discussions about increasing our global resilience to volcanic eruptions.[58]

One problem we face in the potential mitigation of volcanic eruptions is that little is known about which volcanoes are capable of causing global disruption and climatic feedbacks. Global volcanoes are drastically understudied, with estimates suggesting that over 80% of volcanic eruptions capable of causing climate feedbacks are missing from the global geological record.[59] Understanding the eruptive history of volcanoes can help us identify those that are capable of potentially disruptive eruptions, and those that we must closely monitor. However, even if we were able to identify the volcanoes that we need to monitor, currently our ability to do so is limited, particularly as many volcanoes are in resource-limited countries. To date, only 27% of volcanic eruptions have been monitored with ground-based instruments;[60] access to satellite technologies is limited and unable to fill the gaps in global volcano surveillance. In the absence of mitigation measures, volcano monitoring—along with community-based education and preparedness initiatives—are essential for early action and risk reduction, and should be prioritised for funding and development, particularly in pinch-point regions with the highest societal vulnerabilities.

Monitoring and surveillance of volcanoes is just the first step in mitigation and prevention. So, what if we did identify a volcano that may have a large-magnitude eruption—could we do anything to mitigate or prevent it? Interventions with volcanoes themselves (so-called 'volcano geoengineering') are being considered, to assess if we can reduce the impacts of volcanic eruptions.[61] One such project will deliberately drill into a magma pocket within the Krafla Magma Testbed in Iceland, with the aim of providing data on the inner workings of volcanoes to improve our prediction capacities. Manipulating volcanoes is not a new concept; throughout history, we have intervened with volcanoes to reduce the risks posed to local communities. Such examples include the redirection of lava flows through the construction of levees, cooling the moving front with water, and even bombing them. But explosive eruptions are more complicated: their impacts can be global and therefore require global coordination and inclusion in discussions on how we can (and if we should) mitigate and prevent them. It is a subject that requires careful navigation, and efforts towards building global coordination in response to large-magnitude eruptions should be prioritised. For now, volcano geoengineering remains largely theoretical,[62] but with an increasing demand for renewable energy sources, geothermal exploration is putting humanity in closer contact with volcanoes. A natural progression of these explorations may advance our progress on physical interventions with volcanoes, but there must be careful consideration of the ethics of such advancements.[63]

The lesson we can draw from both planetary defence and volcanic eruption mitigation is that, although the technologies for mitigating and preventing both risks provide hope for the future, they remain decades away. In the meantime, humanity remains vulnerable to both asteroid impact and large-magnitude volcanic eruptions, at greater frequencies than previously considered. Our last remaining defence against such risks is preparedness. Building resilience to global critical systems can help prevent cascade impacts and system failures, and utilising tools like scenario exercises can help stress-test and strengthen our response mechanisms. However, civil protection remains our best defence when faced with such risks, and efforts for community-level resilience-building and early action should be prioritised.

Conclusion

The geological record demonstrates humanity's vulnerability to natural catastrophic risks, and shares insights as to our fate if we are unable to prevent or mitigate an impending natural catastrophe. Anthropogenically driven climate change and continued globalisation are changing humanity's relationships with natural risks, potentially pushing some natural hazard events into the realms of global disaster causation. The low prioritisation for mitigation and prevention of natural risks (with the exception of a modest budget assigned for NEO impacts) is not consistent with the threats these risks may pose. With advancements in surveillance and identification technologies for natural risks, we may be able to provide ourselves with a chance to change the course of our future. Lessons can be learnt for other GCRs from fields like planetary defence, demonstrating the importance of global cooperation for the mitigation and prevention of global risks. However, many of the technologies that may one day save us remain decades away from being deployed, therefore efforts for civil protection through a properly constructed resilience strategy may have substantial societal benefits.

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