# Assessing Natural Global Catastrophic Risks

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**Abstract**
The risk of global catastrophe from natural sources may be significantly larger than previous analyses have found. In the study of global catastrophic risk (GCR), one line of thinking posits that deep human history renders natural GCRs insignificant. Essentially, the fact that natural hazards did not cause human extinction at any previous time makes it unlikely that they would do so now. This paper finds flaws in this argument, refines the theory of natural GCR, analyzes the space of natural GCRs, and presents implications for decision-making and research. The paper analyzes natural climate change, natural pandemics, near-Earth objects (asteroids, comets, and meteors), space weather (coronal mass ejections, solar flares, and solar particle events), stellar explosions (gamma ray bursts and supernovae), and volcanic eruptions. Almost all natural GCR scenarios involve important interactions between the natural hazard and human civilization. Several natural GCR scenarios may have high ongoing probability. Deep human history provides little information about the resilience of modern global civilization to natural global catastrophes. The natural GCRs should not be dismissed on grounds of deep human history. Work on natural GCRs should account for their important human dimensions. A case can even be made for abandoning the distinction between natural and anthropogenic GCR.

**Keywords:** global catastrophic risk; climate change; pandemics; near-Earth objects; space weather; stellar explosions; volcanic eruptions

## 1. Introduction

If humanity faced major threats to its survival, then why are we still here? Our ability to (for example) read and write papers on catastrophic risks is wholly dependent on the non-occurrence of any prior catastrophe that would have destroyed the human species. Had such a catastrophe occurred, we would be dead, or our ancestors would be dead and we never would have been born in the first place. The fact of our continued existence tells us something about the ongoing risks that humanity faces. However, as this paper will argue, it does not tell us as much as one might think.

In the study of global catastrophic risk (GCR; defined below), a common approach to accounting for the non-occurrence of prior catastrophes is to distinguish between natural and anthropogenic risks (Bostrom 2013; Millett and Snyder-Beattie 2017; Snyder-Beattie et al. 2019; Ord 2020). Here is the main idea: The human species has existed for roughly 200,000 years, and our hominin ancestors for even longer. Throughout this time, our lineage has faced natural threats such as asteroid collisions and volcanic eruptions. These threats persist today, but the fact that they did not eliminate our ancestors suggests that they are unlikely to eliminate us. In contrast, anthropogenic risks such as nuclear weapons did not exist until quite recently. The assessment of anthropogenic risks is therefore unconstrained by deep human history, implying potential for these risks to be substantially larger.

This paper aims to unpack and critically evaluate this perspective on natural GCRs and to present a new, more refined perspective. The paper proceeds in two main directions. First, the paper reexamines the theoretical perspective outlined above, questioning the strict delineation between natural and anthropogenic risks and the ethical emphasis on human extinction events. Accounting for the interplay between natural hazards and human civilization and for the ethical importance of civilization collapse events, the theoretical case for believing natural threats to pose low GCR weakens substantially. In short, the human species's 200,000 year track record of survival tells us little about modern civilization's resilience to natural global catastrophes. Second, the paper applies this refined theory to a survey of natural GCRs, including natural climate change, natural pandemics, near-Earth objects (NEOs), space weather, stellar explosions, and volcanic eruptions. The survey finds significant interaction between natural hazards and human civilization in ways that could threaten civilization collapse or worse. Although full quantification of these risks is beyond the scope of the paper, the paper does provide reason to believe that the risk from natural GCRs may be substantially larger than has previously been posited.

This paper responds to previous scholarship that has downplayed the threat of natural GCRs at least in part for the reasons outlined above. The most detailed examples of such scholarship are Snyder-Beattie et al. (2019) and Ord (2020); additional examples include Bostrom (2013) and Millett and Snyder-Beattie (2017).[1] In contrast, Manheim (2018) argues that the risk of natural pandemics has been underestimated. This paper is consistent with the perspective of Manheim (2018), augmenting its argument with new theoretical discussion and applying it to a wider range of natural GCRs. More generally, this paper contributes to ongoing scholarship on the methodological basis of evaluating GCRs (Tonn and Stiefel 2013; Avin et al. 2018; Liu et al. 2018; Baum 2020; Beard et al. 2020; Cotton-Barratt et al. 2020) and on comparative GCR assessment (Leggett 2006; Pamlin and Armstrong 2015), especially comparative assessment for catastrophes that do not rapidly result in human extinction (Baum et al. 2019; Kuhlemann 2019; Denkenberger et al. 2021).

## 2. Theoretical Foundations

### 2.1 Inferring Catastrophe Probabilities From Historical Data

We begin with an elaboration of the theoretical argument for a low probability of natural GCR outlined in the Introduction.

For sake of discussion, suppose that the human species materialized out of thin air 200,000 years ago. Obviously this is incorrect; human evolution was (and still is) a gradual process that traces all the way back to early-Earth abiogenisis. However, assuming a fixed starting point simplifies the analysis without loss of generality. Suppose further that, for the entire 200,000 year duration of human history, humanity has faced a single, constant extinction risk. We can assume that the risk is of collision between Earth and a massive asteroid; the particulars are unimportant. This risk is constant in the sense that for each time t, the collision occurs with a probability $p(t)=P$ for some constant P. In other words, the asteroid has the same probability of colliding with Earth in one year as it does in any other year. Given that humanity has not yet gone extinct, what is the value of P?

The situation here is one of zero failure data, meaning a situation in which the failure mode has not previously occurred. Prior literature has proposed several formulae for quantifying probabilities under zero failure data (Bailey 1997; Quigley and Revie 2011), some of which[2] are broadly of the form:

$$P = \frac{1}{3n} \tag{1}$$

[1] Bostrom (2013), Snyder-Beattie et al. (2019), and Ord (2020) do consider some of the points raised in this paper. For example, Bostrom (2013) briefly considers evidence other than deep human history; Snyder-Beattie et al. (2019) briefly considers the interplay between natural GCRs and artificial systems; Ord (2020) does both in greater detail.

[2] Equation (1) corresponds to Equation 9 of Bailey (1997). Equation 20 of Quigley and Revie (2011) is similar, using 2.5 instead of 3 in the denominator.

In Equation (1), n is the number of time periods that have elapsed without a failure event. Thus, for n=200,000, it follows that $P \approx 2x10^{-6}$. In other words, given that there have been 200,000 years with no human extinction event, the probability of humanity going extinct in any given year is approximately $2x10^{-6}$. That is a rather small number, so it may be helpful to consider the probability per millennium instead of per year. Given that there have been 200 millennia with no extinction event, the probability of humanity going extinct in any given millennium is approximately 0.002, or 0.2%. That is indeed a small probability.

A caveat is that our ability to do this analysis depends on humanity's continued existence. This introduces a bias into the zero failure data: had a failure occurred, we would not exist. As a consequence, estimates of P obtained from approaches such as that of Equation (1) will be too low.[3] Snyder-Beattie et al. (2019) explore several techniques for adjusting P to remove this bias, finding that the net effect on P is small. Assessment of this finding is beyond the scope of this paper. For present purposes, Equation (1) suffices.

Equation (1) appears to have strong implications for the assessment of natural and anthropogenic GCR. Natural risks have been present throughout human history and therefore may, in aggregate, have a probability no higher than something on the order of $10^{-6}$ per year as per the calculations above. In contrast, anthropogenic risks are newer. For example, the first nuclear weapon was built in 1945, 77 years ago. Using Equation (2), that implies a probability of approximately $4x10^{-3}$ per year, which is three orders of magnitude higher than the natural risk. This reasoning has factored significantly in some studies concluding that the GCR from natural sources is substantially lower than the anthropogenic GCRs (Bostrom 2013; Millett and Snyder-Beattie 2017; Snyder-Beattie et al. 2019; Ord 2020). The most detailed of these is Snyder-Beattie et al. (2019), which calculates an upper bound for the probability of human extinction from natural sources at approximately $7x10^{-5}$ per year. The distinction between the $2x10^{-6}$ per year calculated above and the $7x10^{-5}$ per year calculated by Snyder-Beattie et al. (2019) does not affect the analysis of this paper: both are very low probabilities calculated exclusively by humanity's 200,000 year lifetime. Furthermore, measuring humanity's lifetime as being longer than 200,000 years makes the probabilities even lower.

### 2.2 The Ethics and Definition of Global Catastrophic Risk

Why focus on the risk of human extinction or global catastrophe in the first place? And how is GCR[4] defined?

Scholarship on GCR tends to be motivated by a certain ethical perspective that emphasizes the importance of extreme catastrophes to the future occurrence of ethical value. Early work by Sagan (1983) and Parfit (1984) argues that because human extinction is forever, accounting for future impacts renders extinction to be of utmost importance. A catastrophe leaving even just a few survivors leaves hope for the future and is therefore comparatively unimportant. Modern scholarship recognizes that this is an incomplete picture because it neglects to account for the variety of trajectories that survivor populations could proceed in, and therefore considers a wider range of global catastrophe scenarios that could affect the long-term trajectory of human civilization (Bostrom 2013; Maher and Baum 2013; Baum et al. 2019; Ord 2020).[5]

The underlying ethical basis for this perspective can be formulated in a variety of ways.[6] The most common ethical basis is standard utilitarian consequentialism, in which utility is weighted equally (i.e.,

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3 For detailed discussion, see Ćirković et al. (2010).

4 The term "existential risk" is sometimes also used in this context (Bostrom 2013; Tonn and Stiefel 2013; Ord 2020). Any distinction between this term and GCR is unimportant for purposes of this paper.

5 Civilization can be defined as a population with "a relatively high level of cultural and technological development" (Merriam-Webster n.d.).

6 See Tonn (2002; 2018), Baum et al. (2019), and Ord (2020) for ethical bases that differ from that presented here.

undiscounted) across space and time, and in which uncertainty is handled via maximizing expected utility:

$$D(x)=E\left[\int_{t=1}^{T} u(x,t)\partial t\right] \tag{2}$$

Equation (2) shows decision parameter D as a function of decision option x. The decision problem is to identify the option(s) x that maximizes D. D is obtained by taking the expected value E of the integral of utility u across time t=1:T. The final time T defines the time horizon. In principle, T should be infinity, but that raises mathematical complications that are unimportant for present purposes, so, for convenience, we can assume T is finite but extremely large, e.g. $10^{100}$ years. In the moral philosophy of utilitarianism, utility is commonly defined as either the quality of subjective experience (e.g., pleasure/pain) or the satisfaction of preferences (Broome, 1991; Kahneman & Sugden, 2005; Ng, 2003); this distinction is also unimportant for present purposes.

Equation (2) presents a very basic moral framework that is in wide use in ethics, economics, policy analysis, and related fields. However, it has some profound implications that are not always recognized. By maintaining a principle of equality across space and time and by stretching the time horizon out to the very distant future, Equation (1) welcomes consideration of outcomes on astronomical scales. Earth will remain habitable for roughly one billion years, until the Sun becomes too warm (O'Malley-James et al., 2014; Wolf and Toon, 2015).[7] The rest of the universe may remain habitable for far longer. A spacefaring civilization could persist across time and also expand immensely across space. The amount of value at stake utterly dwarfs the more immediate Earthly considerations that are typically the focus of human affairs.

GCR can now be defined as the risk of a catastrophe so severe that it would cause a significant reduction in the long-term, astronomical-scale expected value of human civilization.[8] Figure 1 shows several ways in which this could happen, via catastrophes that either cause human extinction, cause a collapse of civilization in which survivors never recover civilization,[9] or cause a significant delay in astronomical expansion. All of these scenarios can involve significant reductions in the long-term trajectory of human civilization as measured in terms of Equation (1).[10] It should be emphasized that Figure 1 is just a rough sketch of some potential scenarios; it is neither a precise calculation of any specific scenarios nor a comprehensive compilation of scenarios.

It is certainly possible to care about GCR without caring about the long-term future.[11] The immediate and short-term harms of global catastrophes can be significant in their own right (Posner 2014; Baum 2015); this corresponds to a small time horizon T in Equation (2). For reasons explained below, the arguments of this paper are strengthened by a more short-term ethical framework.

### 2.3 Natural and Anthropogenic Global Catastrophic Risks

7 Intervention from intelligent civilization could extend Earth's habitable lifetime, such as by blocking a portion of incoming solar radiation. The habitable lifetime could conceivably be extended indefinitely by relocating Earth further from the Sun, though at that point it may be easier to find other places to live.

8 This definition is slightly different from, and arguably more normatively precise than, other long-term focused definitions of GCR and existential risk (e.g., Yassif 2017; Ord 2020). Other literature has defined GCR and existential risk in other ways. For a compilation of definitions, see Baum and Barrett (2018, Section 2).

9 Civilization collapse can be defined as an event resulting in a large loss of a population's cultural and technological development, potentially but not necessarily including a large decline in the size of the population.

10 For more detailed discussion of these trajectories, see Bostrom (2013), Maher and Baum (2013), and in particular Baum et al. (2019).

11 For debates over caring about the future, see e.g. Laslett and Fishkin (1992); Weisbach and Sunstein (2007).

What exactly is the distinction, if any, between natural and anthropogenic GCRs?

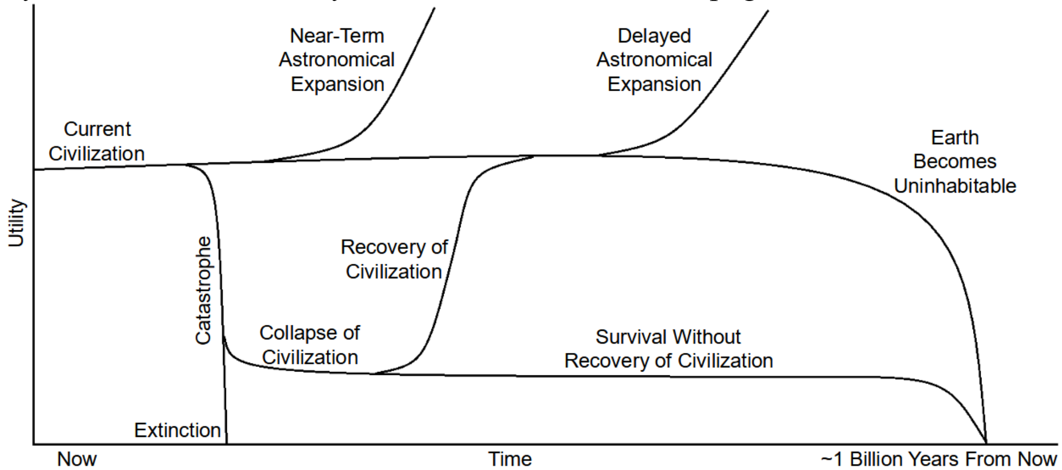


**Figure 1.** Sketch of select long-term trajectories of human civilization.

There is a sense in which all GCRs are natural. Humans are not supernatural; we are part of nature, composed of the same atoms and molecules and subject to the same physical laws as everything else. The same applies to artifacts of human activity such as art and technology. Humans are likewise members of ecosystems and cannot otherwise survive.[12] There is a longstanding and unfortunate tendency to believe otherwise, that the human sphere is somehow separate from "nature". This results in a variety of apparent epistemic and ethical errors (Latour 1993; Curry 2011). The faulty cultural construct of a nature/society binary may underlie some of the tendency to de-emphasize natural GCRs, though that is beyond the scope of this paper.

For present purposes, a rough distinction between natural and anthropogenic GCRs can be made—and then, to a significant extent, unmade. The distinction involves the origin of the hazard. Hazards such as asteroids and comets are not produced by human activity, whereas hazards such as nuclear weapons and industrial greenhouse gas emissions are produced by human activity. All of these hazards are "natural" in the sense of being part of nature, but only some of them are "natural" in the sense of not being caused by humans.

Some complications arise. The complications can be classified in terms of the hazard/exposure/vulnerability conceptualization of risk.[13] The hazard is the source of the danger; the exposure is the population subject to the hazard; and the vulnerability is extent of harm the exposed population is likely to endure. For the hazard, humans can play a role in some GCRs commonly classified as natural, such as human activity that causes or fails to prevent an asteroid from colliding with Earth (Harris et al. 1994; NRC 2010). For the exposure, human activity can play a role, such as in the development of refuges that keep their inhabitants out of harm's way (Baum et al. 2015; Boyd and Wilson 2021). For the vulnerability, human activity can play a role, such as in the resilience of global economic and infrastructure systems to the disturbances of the catastrophe event (Helbing 2013; Centeno et al. 2015). It is well established that human vulnerability to more moderate, non-GCR natural hazards depends on a variety of social factors such as wealth, age, race, and housing quality (Cutter et al. 2003). For natural GCR hazards, unless the hazard is so extreme that it would immediately kill all humans regardless of what humans tried to do to survive, the ultimate severity of

[12] With some imagination, one can conceive of technology that could plausibly enable human bodies to survive without support from anything that would classify as an ecosystem. Suffice to say, such technology does not currently exist.

[13] Risk as hazard/exposure/vulnerability is a common framework; for its application to GCR, see Liu et al. (2018). Recent research has proposed a fourth category, response, referring to actions taken to reduce risks (Simpson et al. 2021). This paper classifies response actions within the hazard/exposure/vulnerability framework, such as in actions taken to reduce vulnerability.

the event would hinge on human activity.

The specific roles of human activity in natural GCRs are explored further in Section 3. For now, it suffices to observe that many "natural" GCRs are in important respects not entirely "natural".

**2.4 Refining the Theory of Natural Global Catastrophic Risk**

Synthesizing the above ideas, an improved perspective emerges.

Section 2.1 presented an argument that natural GCRs are low probability based on the observation that no natural catastrophe caused human extinction at any point in humanity's 200,000 year history. The argument is rooted in an assumption that the risk from natural GCRs is constant over time. But what if it is not constant? Then analysis of deep human history may not yield the conclusion of low risk from natural GCRs.

There are two types of change that could cause the risk from natural GCRs to vary over time. The first is change in the natural hazard. The natural universe is dynamic and its hazards do change over time. Nonetheless, it may be reasonable to expect natural hazards to be approximately constant over the time scales of human history. It would be an unlikely coincidence for the hazards to happen to intensify just as human civilization is emerging. The second and more important type is change to human civilization. The current human population is radically different than the population that existed for the vast majority of human history. As Section 2.3 explains, natural hazards can interact with human civilization in important ways, such that the resulting GCR is not strictly "natural". To the extent that natural GCRs interact with human civilization, evidence from deep human history is of limited relevance. Section 3 presents examples of both types of changes.

The ethics of GCR further underscores the importance of interactions between natural hazards and human civilization. Section 2.1 focused exclusively on human extinction. However, Section 2.2 shows that other catastrophe scenarios, such as the collapse of civilization, can be of comparable moral importance. Most of human history is of minimal relevance to the collapse of civilization because civilization is a relatively recent phenomenon. Civilization in any form has only existed for approximately 10,000 years; modern global civilization is radically different from what existed for most of the history of civilization and it is changing rapidly.

An important analytical parameter is the comparative importance of extinction vs. collapse scenarios. Revisiting Figure 1, following collapse there is some probability of recovery and eventual astronomical expansion. Therefore, the expected harms of collapse are smaller than the expected harms of extinction, as calculated by Equation (2). But how much smaller? This is a major point of uncertainty on which little analysis has been done. Bostrom (2013) and Ord (2020) briefly argue that survivors of collapse scenarios are very likely to have a full recovery in most cases, whereas a more detailed analysis by Baum et al. (2019) is less optimistic about survivors' prospects. Which perspective is correct is beyond the scope of this paper. Instead, this paper models the relative importance of extinction and collapse scenarios as follows:

$$w(c)=\frac{\Delta E\left[\int_{t=1}^{T} u(c,t)\partial t\right]}{\Delta E\left[\int_{t=1}^{T} u(\Omega,t)\partial t\right]} \tag{3}$$

Equation (3) defines w(c) as the long-term moral weight of catastrophe scenario c. The moral weight of an event is defined as the change Δ in expected utility caused by the event. The numerator of Equation 3 is the change in expected utility from c. The denominator is the change in expected utility from a human extinction event Ω. The denominator is a constant used to improve the interpretability of w. A catastrophe $c_1$ in which $w(c_1)=1$ has the same long-term severity as human extinction. For some non-extinction collapse scenario $c_2$, the claim that $c_2$ is of negligible long-term moral significance can be expressed as $w(c_2)\approx 0$. Conversely, the claim that $c_2$ is of large long-term moral significance, but less long-term moral significance than extinction, can be expressed as $0 \ll w(c_2) < 1$.[14]

Suppose, for sake of discussion, that the long-term trajectory is the same for all catastrophe scenarios that result in civilization collapse and do not result in human extinction. Let $c_c$ be a representative collapse scenario. If $w(c_c)$ is small, then natural GCRs are likely to be comparatively small, following the reasoning of Section 2.1. Conversely, if $w(c_c)$ is large, then the reasoning of Section 2.1 is largely inapplicable and natural GCRs may be comparatively large. Obtaining the exact size of natural GCRs would require analyzing the risks as they currently exist and not relying on deep human history.[15] In practice, w may not be the same for all catastrophe scenarios, in which case the overall evaluation of natural GCRs requires aggregating across natural catastrophe scenarios.

Even if $w(c_c)$ is small, it is still possible that natural GCRs could be large. Strictly speaking, natural GCRs could be large if it is mere coincidence that earlier humans did not go extinct. However, this is unlikely for reasons outlined in Section 2.1. Alternatively, changes to the human population could make it more likely to go extinct in the event of a natural global catastrophe. For example, one can imagine a hypothetical future population with zero subsistence farmers and a catastrophe event in which civilization collapses and the only way to survive is through subsistence farming. Conversely, even if $w(c_c)$ is large, it is still possible that natural GCRs could be small. Perhaps the natural hazards needed to cause collapse just happen to be rare.

To sum up: There is a portion of natural GCRs for which deep human history implies a low ongoing risk and a portion of natural GCRs for which deep history is of limited relevance. If collapse scenarios are ethically significant (i.e., if $w(c_c)$ is large), then natural GCR is likely to be comparatively large and deep history is of less relevance. Evaluation of natural GCR requires analysis of the natural GCRs themselves and of human exposure and vulnerability to them; historical arguments alone are insufficient.

Finally, the discussion above assumes an ethical concern for the long-term future. If one instead has a short ethical time horizon, the analysis is simpler: w(c) would be the short-term harm of the catastrophe compared to the short-term harm of extinction, using some small T in Equation (3). A catastrophe that (for example) killed half the global human population might have $w(c)\approx 0.5$. Such a catastrophe would be less ethically significant than an extinction catastrophe, but not radically less significant in the way suggested by some scholarship focused on long-term outcomes. Likewise, natural GCRs could still be of high ethical significance even if they only pose low extinction risk. Unless otherwise stated, the analysis below assumes a concern for the long-term future.

## 3. The Natural Global Catastrophic Risks

This section surveys several important classes of natural GCR in terms of the theory presented in Section 2. In particular, the analysis addresses the relevance of deep human history, interconnections between natural and human systems, and the overall size of the GCR, including the risk of civilization collapse. Space constraints preclude comprehensive analysis. Omitted items include effects on long-term trajectories (w in Equation (3)) and quantification of the risks; these items require analysis that

14 Denkenberger et al. (2021) include parameters on the reduction in the long-term value of human civilization caused by some catastrophe event, which is similar to w(c). Denkenberger et al. (2021) quantify the parameters via a survey of attendees at a conference presentation. This quantification should be viewed skeptically due to the high complexity and uncertainty about the parameters and the limited information provided about the survey participants; for related discussion of parameter quantification, see Morgan (2014) and Beard et al. (2020).

15 The size of $w(c_c)$ is also important for anthropogenic GCRs that cause collapse but not extinction.

goes significantly beyond the basic character of the risks.[16]

### 3.1 Natural Climate Change

Natural climate change factors significantly in the ethics of GCR. In particular, the gradual warming of the Sun over approximately one billion years structures the potential long-term trajectories of civilization (Figure 1). Natural climate change has also been important within deep human history. Glacial-interglacial cycles occur on time scales of around 100,000 years (Archer 2008). The onset of the favorable climate of the Holocene interglacial approximately 10,000 years ago may have been crucial for the rise of human civilization (Richerson et al. 2001).

In theory, natural glaciation could threaten civilization. If the Holocene interglacial was crucial for the rise of civilization, the end of the Holocene could induce the fall of civilization. Furthermore, only one other interglacial occurred during the 200,000 year lifetime of the human species, the Eemian, approximately 130,000 to 115,000 years ago (Dahl-Jensen et al., 2013). There are only two data points of humans surviving glacial-interglacial cycles and zero data points of human civilization surviving them. Deep human history provides minimal confidence about the resilience of human civilization or the human species to glacial-interglacial cycles.

In practice, natural glaciation is not an imminent concern. Greenhouse gas emissions are projected to extend the current interglacial period for 30,000-500,000 years (Archer and Ganopolski 2005; Herrero et al. 2014). The ability of the human species or human civilization to survive anthropogenic global warming is an open question (Beard et al. 2021).

### 3.2 Natural Pandemics

The distinction between natural and anthropogenic pandemics is particularly blurry. One distinction is between pathogens that arises in nature and pathogens created via biological science and technology, such as gain-of-function experiments and DNA synthesis (Millett and Snyder-Beattie 2017). However, human activity can cause the onset of "natural" pandemics, such as when interactions with wildlife cause pathogens to jump from a nonhuman species to humans (i.e., zoonosis; Morse et al. 2012). The risk from wildlife zoonosis may be larger now than during early human history because the larger human population has more points of contact with wildlife. Additionally, zoonosis can also occur in factory farms, a setting that exists in the grey area between natural and anthropogenic (Manheim 2018).

Once the pathogen has infected humans, it is spread primarily via human activity.[17] The risk is heavily affected by modern global civilization. On one hand, modern medicine and public health creates more powerful techniques for reducing the severity of pandemics. On the other hand, global travel and urban density create more opportunities for pathogens to spread. Earlier in human history, a catastrophic natural pathogen may have only killed off a smaller, isolated portion of the population, leaving no clear archaeological record, whereas the same pathogen could cause global catastrophe (Manheim 2018). Therefore, the deep historical evidence is consistent with even a high ongoing probability of human extinction from natural pandemics, implying that natural pandemic risk can be of large long-term moral importance even if $w(c_c)$ is small.

Pandemics could further threaten civilization collapse. Pandemics could disrupt the labor pool, causing acute supply chain disruptions with severe effects such as to food security (Huff et al. 2015). A pandemic causing neurological harm, such as in long COVID (Misra 2021), could result in the human population having insufficient cognitive fitness to maintain civilization. Furthermore, these sorts of effects could have occurred during pandemics earlier in human history without leaving a noticeable trace. Supply chain disruptions would have been of minimal consequence for most of human history.

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[16] On analysis for long-term trajectories, see Baum et al. (2019); for quantification, see Beard et al. (2020).

[17] The dynamics of pathogen spread apply to both natural and anthropogenic pathogens, to the extent that the two categories can be distinguished.

Medical effects such as neurological harm could go away, for example, if it is not passed to subsequent generations. If $w(c_c)$ is large, the potential effects of pandemics on civilization collapse merit careful scrutiny.

One particularly complex and acute pandemic scenario is when a pandemic causes a failure of stratospheric geoengineering. Stratospheric geoengineering involves injecting particles into the stratosphere to counteract the harms of anthropogenic global warming. If particle injection is abruptly halted, temperatures rapidly rise, which could cause acute harm known as termination shock (Parker and Irvine 2018). Under normal circumstances, abrupt cessation of particle injection may be unlikely due to the desire to avoid termination shock. However, Baum et al. (2013) propose that a catastrophe such as a pandemic could cause the cessation of particle injection, resulting in a "double catastrophe" in which the harms of termination shock compound the harms of the initial catastrophe. This may be an especially severe pandemic scenario. It is also a scenario rooted in interactions between the natural hazard and human civilization. Further complicating the picture, prior to termination shock, stratospheric geoengineering could shift climates in a way that shifts disease vector patterns, potentially affecting the risk of "natural" pandemics (Tang and Kemp 2021).

Fan et al. (2016) estimate an annual probability of $1.6 \times 10^{-2}$ for "severe" pandemics defined as pandemics that cause the death of 0.1% of the global human population. The ongoing COVID-19 pandemic is estimated to already exceed this threshold.[18] Thus far, fortunately, COVID-19 has not threatened the collapse of civilization or human extinction. Therefore, the annual probability of pandemics that threaten collapse or extinction is likely to be lower than $1.6 \times 10^{-2}$, with the collapse probability being higher than the extinction probability, though the exact probabilities are difficult to quantify (Manheim 2018). Nonetheless, there is potential for this risk to be significantly higher than the $2 \times 10^{-6}$ annual probability calculated in Section 2.1.

### 3.3 Near-Earth Objects

NEOs refer to asteroids, comets, and meteoroids whose orbits come within 1.3 astronomical units from the Sun. Large NEOs are less numerous and collide with Earth less frequently, but the severity of the subsequent physical hazard is larger. Large NEOs are also easier for astronomy to detect. Upwards of 90% of large NEOs have already been detected; the percentage is lower for smaller NEOs (Mainzer et al. 2011; 2014; Harris et al. 2015). No detected NEO is on an Earthbound trajectory. If an Earthbound NEO is detected, there are proposals for space missions to deflect it away from Earth (NRC 2010).

NEO risk can be anthropogenic. It has been proposed that space missions could be used to intentionally redirect harmless NEOs toward Earth (Harris et al. 1994). In this scenario, the hazard would not exist except for human activity, so it would classify as anthropogenic. However, this scenario appears to be unlikely: anyone wishing to cause harm on Earth would have easier means of doing so.

The hazard of natural NEO collision has gradually changed over time. The frequency of Earth-NEO collisions is believed to have declined over the history of the solar system due to increased stability of planetary orbits and the accretion (i.e., merging together) of smaller asteroids (NRC 2010, p.12). Accretion shifts the risk from smaller, more frequent collisions to larger, rarer collisions and therefore may constitute a net increase in the risk. Regardless, the change in the hazard appears to be gradual enough that the hazard is approximately constant over the time scales of human history such that it would not complicate the sort of analysis presented in Section 2.1. A larger effect could come from

[18] Under the current world population, the threshold for severe pandemics is approximately 7.8 million deaths. As of 8 January 2022, official World Health Organization statistics, https://covid19.who.int, show approximately 5.5 million deaths from COVID-19, but this omits undocumented cases. Accounting for undocumented cases, the Institute for Health Metrics and Evaluation of the University of Washington School of Medicine, https://covid19.healthdata.org, estimates a total of approximately 12.7 million deaths.

programs to deflect Earthbound NEOs away.

Human vulnerability to NEO collision has changed more substantially. Large NEO collisions can cause global firestorms, ozone layer damage and accompanying increased ultraviolet radiation, and reduced surface temperatures and precipitation and accompanying declines in vegetation (Toon et al. 1997; 2016). The declines in vegetation could threaten global famine. For large enough collisions, civilization collapse or human extinction could occur, though the human consequences have not been studied closely and remain deeply uncertain (Baum 2018). The collision size needed to cause collapse is presumably smaller than the size needed to cause extinction. Smaller collapse-scale NEOs collide with Earth more frequently. It is plausible that humans could have survived 200,000 years of frequent collapse-scale collisions, whereas modern civilization faces a large ongoing risk from them.

Global catastrophe could be caused by much smaller NEOs via inadvertent nuclear war. NEO collisions cause explosions of magnitude proportionate to their diameter. NEO collisions of comparable explosive force as nuclear weapons are small and occur more frequently, roughly on time scales of years to decades.[19] Baum (2021) documents seven incidents between 1990 and 2018 in which an NEO collision prompted some sort of military reaction and proposes that a similar incident could be misinterpreted as a nuclear attack, prompting nuclear war. The probability of such an incident resulting in nuclear war and in turn global catastrophe is uncertain, but the high frequency of near-miss events suggests potential for a large GCR. This scenario is one in which there is no meaningful distinction between natural and anthropogenic GCR.

### 3.4 Space Weather

Space weather refers to certain events that occur within the Sun and that can then affect Earth, in particular solar flares, which are rapid bursts of electromagnetic radiation, coronal mass ejections, which are large releases of material, and solar particles events, which are emissions of high-energy particles (Eastwood et al. 2017; Oughton 2021).

Rare, intense space weather events can cause biological harm. Lingam and Loeb (2017) propose that extreme “superflares” could cause mass extinction via acute ozone depletion, abrupt temperature increase, and acid rain. Many biological species are vulnerable to these hazards, and so Lingam and Loeb (2017) postulate that their occurrence causes mass extinction events. Following Raup and Sepkoski (1984), Lingam and Loeb (2017) consider a mass extinction rate of roughly once per 20 million years and find that this rate is consistent with data on superflares from Sun-like stars observed by the Kepler space telescope. A 20 million year frequency corresponds to an annual probability of $5 \times 10^{-8}$, which is considerably lower than (and consistent with) the $2 \times 10^{-6}$ annual probability of human extinction from natural hazards calculated in Section 2.1. However, some research has questioned whether the Sun is capable of producing superflares (Aulanier et al. 2013); ongoing analysis of Kepler data remains inconclusive on this matter (Notsu et al. 2019).

The story is radically different for more moderate, frequent space weather events. For these, the biological harm is negligible. Instead, the primary effects are to technology, including disruptions to electrical power networks, oil and gas pipelines, satellites, railroad networks, and aviation (Eastwood et al. 2017). A common point of comparison is to the 1859 space weather event named after astronomer Richard Carrington, which disrupted telegraph systems. A 1921 event has been found to be of comparable magnitude (Love et al. 2019). Events of this magnitude are estimated to occur approximately once per 100 years (Riley 2012), once per 150 years (Chapman et al. 2020), or once per 500 years (Yermolaev et al. 2013), though Chapman et al. (2020) caution that the frequency estimates may be inapplicable if the Carrington event derived from atypical solar processes. Impacts studies have focused on economic effects if such an event were to occur now, finding damages as high as trillions of

[19] Compare Baum (2021, Section 4.2) to Harris et al. (2015, Figure 2).

dollars and recovery times of several years, with significant disagreement between studies and important effects not yet considered (Oughton 2021). The tone of the existing work does not suggest civilization collapse as a potential outcome, though the matter has not been explicitly studied. Furthermore, the effects of more extreme events, such as those that may occur once per 1,000 or 10,000 years, have also not been studied as closely. Recent evidence indicates that more extreme space weather events occurred in years 660 BCE, 775 CE, and 994 CE (Usoskin and Kovaltsov 2021). Were a similar event to occur now, the effects on human civilization could be very severe.

Space weather could further risk global catastrophe via interactions with high-stakes technologies. Two possibilities have been proposed. First, space weather could interact with electrical systems involved in the nuclear weapons enterprise, causing false alarms and inducing inadvertent nuclear war. A precedent is a 1967 solar storm that caused interference at the US Ballistic Missile Early Warning System in Alaska, causing US forces to suspect Soviet radar jamming in advance of an attack (Knipp 2016). Second, space weather could damage the systems needed for stratospheric geoengineering, causing a termination shock and the accompanying double catastrophe (Tang and Kemp 2021).

Moderate space weather events are notable because they would have caused approximately zero harm for the vast majority of human history. Harm has only been possible since the industrial revolution and has become especially pronounced since the rise of electrical power networks. Clearly, this is a risk in which the natural/anthropogenic distinction has little meaning. Furthermore, space weather effects several systems that are critical for modern civilization and may therefore pose a high risk of collapse. Loper (2019) proposes that civilizations have a narrow window of time between major space weather events in which they must either harden infrastructure to withstand space weather or expand beyond the home planet. A high GCR from space weather is consistent with the 200,000 year history of human survival, especially if $w(c_c)$ is large.

**3.5 Stellar Explosions**

Stellar explosions are events, including supernovae and gamma-ray bursts, that release massive amounts of energy. These events would destroy most or all living beings within a large portion of the galaxy (Vukotić and Ćirković 2007). There are plausible mechanisms for protecting a civilization from this hazard, but they involve engineering projects at astronomical scales and therefore are beyond the capacity of current human civilization (Ćirković and Vukotić 2016). Stellar explosions that threaten Earth are exceptionally rare; Melott et al. (2004) estimate an annual probability of $3 \times 10^{-9}$. Therefore, stellar explosions are consistent with low natural GCR as calculated in Section 2.1.

**3.6 Volcanic Eruptions**

In a process similar to that of large NEO collisions, the primary effect of volcanic eruptions is to send sulfur gas into the stratosphere, which then converts to sulfate aerosol droplets and remain aloft for months to years, thereby reducing surface temperatures and precipitation (Robock 2000; Timmreck 2012). For sufficiently large events and potentially depending on the human response, this process could induce famine. Eruptions also produce ash that generally does not reach the stratosphere and returns to the surface within days. Also similar to NEO collisions and other risks, collapse-scale events are likely to be more frequent than extinction-scale events.

The massive eruption of Mount Toba (now Lake Toba, Indonesia) approximately 75,000 years ago is among the most important data points in the study of GCR. Early scholarship hypothesized that the eruption caused a bottleneck in the human population and may have nearly caused human extinction (Ambrose 1998), and some climate modeling has estimated the eruption to have caused extreme global cooling of 8ºC to 17ºC (Robock et al. 2009). However, more recent scholarship points to a less severe event, including archaeological evidence of hominin survival in India (Petraglia et al. 2012) and climate modeling finding more moderate temperature declines less than 4ºC in the portions of Africa where humans lived (Black et al. 2021). The study of the Toba eruption informs the modern understanding of human resilience to global catastrophes, though interpretation of the event should be done in consideration of differences between the human population then and now, in particular with respect to the onset of the large, modern global civilization.

Volcanic eruptions can have significant effects on civilization. This was recently illustrated by the 2010 Eyjafjallajökull eruption, prompted the shutdown of air travel across northern Europe (Budd et al. 2011). Larger disruption could come from larger eruptions, especially those in sensitive locations. Mani et al. (2021) identify seven locations where eruptions could cause outsized harm, such as the Strait of Malaca, a major shipping corridor, and Taiwan, a major semiconductor manufacturer. These locations are important nodes in the global economy; eruptions affecting them could cause significant global disruption. Mani et al. (2021) propose that this could constitute a GCR, though both the immediate and long-term effects of such disruptions remains deeply uncertain.

Rougier et al. (2018) estimates a $6x10^{-5}$ annual probability of "super-eruptions" that erupt at least $10^{12}$ tons of mass.[20] For comparison, Toba erupted approximately $10^{13}$ tons of mass (Rougier et al. 2018), whereas Eyjafjallajökull erupted approximately $5x10^{8}$ tons of mass (Gudmundsson et al. 2012). The super-eruption probability is a bit higher than the $2x10^{-6}$ annual probability of human extinction from natural hazards calculated in Section 2.1, and indeed at least one super-eruption, Toba, occurred during deep human history. In addition to Toba, Rougier et al. (2018, Figure 2) document three eruptions in the last 100,000 years that are at or slightly above their super-eruption threshold: Taupo/Oruanui (New Zealand), Aira (Japan), and Atitlán (Guatemala), as well as one eruption slightly below the threshold, Asosan/Aso-4 (Japan) that other research has described as a super-eruption (Takarada S, Hoshizumi H (2020). The magnitude of erupted mass and the corresponding probability of a collapse-scale eruption has not been studied.

## 4. Discussion

### 4.1 The Blurry Distinction Between Natural and Anthropogenic Global Catastrophic Risks

Human activity factors in a large portion of what might be labeled "natural" GCR. Human activity factors in the onset of the initial hazard in some scenarios, in particular scenarios involving human encounters with natural pathogens and human redirection of NEOs toward Earth. Additionally, in almost all scenarios, human activity factors in the vulnerability of human civilization and the human species to the hazard.

The only scenario in which human activity does not apparently factor is stellar explosions. The natural hazard from stellar explosions is too severe for the current civilization to have any hope of surviving. This scenario is notable across the entire space of natural hazards. In natural hazards research, it is well established that human activity factors centrally in the extent of the harm caused (Cutter et al. 2003). Stellar explosions may be the only natural hazard for which human activity is irrelevant, an extremely low-probability exception to the rule.

For all other "natural" GCRs, the natural/anthropogenic distinction is a rather blurry one. Furthermore, an emphasis on the "naturalness" of the GCR risks inattention to the important human dimensions of natural GCRs. It may even be helpful to abandon the natural/anthropogenic GCR distinction entirely.[21]

### 4.2 The Potentially Large Size of Natural GCR

Several scenarios involving natural GCRs may be especially large in terms of the product of probability

[20] The effects on human populations also depend on other factors such as the relative amounts of sulfate gas and ash produced and the location of the eruption.

[21] Yes, the irony of advocating against the natural/anthropogenic distinction in a paper on natural GCR is noted.

and severity. These include natural pandemics, disruption of critical infrastructure caused by space weather, geoengineering termination shock double catastrophe caused by natural pandemics or space weather, and inadvertent nuclear war caused by NEO collision or space weather. Out of all the scenarios considered in Section 3, these appear to have the most potential for a high risk.[22] All of them involve natural hazards with relatively high annual probabilities, potentially as high as $10^{-2}$ or even higher, with the ultimate severity depending on interactions with human civilization. The exact size of the risk is uncertain and is beyond the scope of this paper, as is the comparative size of these risks to "anthropogenic" GCRs. To clarify, because the exact size of the risk is beyond the scope of this paper, the paper reaches only tentative conclusions about the risk, hence it is stated that some natural GCRs *may* be especially large. There is reason to believe that they may be large, but evaluating this requires further work than can be done in a single paper.

### 4.3 The Low Information Value of Deep Human History

The fact that humans have survived for 200,000 years does provide some meaningful information about the ongoing risk from natural GCRs. Early humans successfully survived 1-2 glacial/interglacial cycles and several large volcanic eruptions. Additionally, the long lifetime of humanity suggests that there are probably not any high-probability natural GCRs in which human survival is effectively impossible. The only known unsurvivable natural GCR is stellar explosions. If there exist any unsurvivable natural GCRs that are not (yet) known, it is reasonable to conclude, based on the long lifetime of humanity, that their probabilities are very low.

For all other natural GCRs, deep human history is at most a weak source of information about the ongoing risk. The human population and civilization have changed too much for the assumption of constant probability in Equation (1) to be reasonable. For some catastrophe scenarios, the risk may have gone down due to the human population being larger and more geographically dispersed and due to the myriad capabilities of modern civilization. For other scenarios, the risk may have gone up due to the various fragilities of modern civilization. Deep human history provides zero information about the many important interactions between natural hazards and modern civilization.

### 4.4 The Analytical Importance of the Long-Term Moral Importance of Collapse Scenarios

The size (probability times severity) of natural GCR may depend heavily on the moral importance of catastrophes in which civilization collapses but humans do not immediately go extinct. Natural pandemics, NEO collisions, space weather, and volcanic eruptions all appear to have higher probabilities for collapse-scale catastrophes than for extinction-scale catastrophes, potentially much higher probabilities. The difference is especially acute for space weather, in which there are relatively high probability scenarios that threaten extreme harm to critical infrastructure but not to human bodies, whereas scenarios that harm human bodies are extremely rare.

Section 2.4 introduced the parameter $w(c_c)$ as the long-term moral weight of civilization collapse in comparison to the long-term moral weight of human extinction. If $w(c_c)$ is large, then natural GCR may also be large, and vice versa for small $w(c_c)$. There are some extinction scenarios involving natural GCRs that may have high probabilities, especially natural pandemics, inadvertent nuclear war induced by NEO collision or space weather, and geoengineering termination shock double catastrophe induced by natural pandemics or space weather. However, even for these scenarios, civilization collapse is presumably more likely than human extinction.

Quantification of $w(c_c)$ is beyond the scope this paper. However, some insight can be obtained from the analysis of Section 3. Bostrom (2013) argues that it is unlikely that there would be recurring cycles of collapse and recovery of civilization: either humanity would go extinct or it would achieve

[22] According to the subjective judgment of the author. Other observers may reach other conclusions.

astronomical expansion, at which point its vulnerability to catastrophes is minimal.[23] One mechanism through which these cycles could occur is found in Loper (2019): Carrington-class space weather events with 100-500 year intervals, which destroy civilizations before they can achieve astronomical expansion but do not cause extinction. In practice, there can be more than one mechanism for inducing collapse; instead, it could be the full suite of natural and/or anthropogenic collapse-scale GCRs. This possibility suggests a relatively high value of $w(c_c)$. However, the absence of data (advanced global civilization has never previously collapsed[24]) and the fact that these scenarios are just beginning to be studied suggests that our understanding of them is poor. In the face of high uncertainty about $w(c_c)$, it may be inappropriate to assume either $w(c_c)\approx 0$ or $w(c_c)\approx 1$. As long as $w(c_c)$ is not $\approx 0$, the risk of collapse from natural GCRs may be morally significant.

The above discussion assumes that the long-term future is morally important. If instead a short time horizon (T) is used for moral evaluation, then the analysis will depend less on the dynamics of collapse and more on the immediate harms of catastrophes.

### 4.5 Implications for Policy and Decision-Making

First and foremost, the threat of natural GCRs should not be dismissed on the basis of deep human history. The fact that humans have survived for 200,000 years provides very little information about the risk faced by modern global civilization. Instead, evaluation of natural GCRs should be rooted in detailed analysis of the risks, including their many important interactions with human civilization.

Second, risk management should de-emphasize the distinction between natural and anthropogenic GCRs. One reason is that the distinction is blurry. Risk management should account for the important human dimensions of natural GCRs. Another reason is that many risk management solutions cut across the GCR space, with benefits for both natural and anthropogenic GCRs, to the extent that any distinction can be made. One important example of this is in solutions to increase the resilience of civilization to global catastrophes, such as by hardening infrastructure, increasing local self-sufficiency, and making contingency plans. These solutions can be of value for a wide range of natural and/or anthropogenic global catastrophe scenarios.

### 4.6 Implications for Research

As a survey of a broad and complex topic, this paper has raised more questions than it has answered. Some directions for future research that appear especially important include evaluating the long-term moral weight of civilization collapse (i.e., quantifying $w(c_c)$), analyzing the natural GCR scenarios with the most potential to be large (Section 4.2), and developing effective risk management solutions. Future research could also study natural GCRs not included in this paper, such as those involving fluctuations in Earth's magnetic field (Palmer et al. 2006) and back contamination of Earth by extraterrestrial pathogens (Stern et al. 2019). This paper's theoretical analysis could be extended to account for observation selection effects (Ćirković et al. 2010), for example by accounting for the non-occurrence of prior catastrophes that would decimate but not eliminate the human population. Additionally, all research on natural GCRs should make a point of including attention to the human dimensions of the risks, with the notable exception of research on stellar explosions.

## 5. Conclusion

To revisit the opening question of this paper: If humanity faced major threats to its survival, then why are we still here? It is rather unlikely that humanity just happened to be exceptionally lucky for 200,000 years. In all likelihood, either there are no major threats to humanity or something has changed. But

[23] Bostrom (2013) makes this point in terms of technological maturity instead of astronomical expansion, but the structure of the idea is the same either way.

[24] On Earth, to our knowledge; but see Schmidt and Frank (2019).

something has changed: humanity. The rise of modern global human civilization creates a plethora of risks that early humans did not face, including risks to the collapse of civilization. In a sense, this is a good thing: civilization creates new opportunities that can be of very high value, the largest of which is the potential for expansion into outer space. However, global catastrophe must be avoided in order to achieve this value. Given the stakes, it is vital that the GCRs be well-understood so that they can be effectively reduced.

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