Climate Change, Uncertainty, and Global Catastrophic Risk

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Abstract
The status of climate change as a global catastrophic risk is a significant point of contention. Some research characterizes climate change as a grave threat to human civilization; other research characterizes it as having relatively mild severity. This article provides a perspective on how to evaluate the considerable uncertainty about the potential for climate change to cause global catastrophe. The article shows that some prior literature has understated the basis for regarding climate change as a global catastrophic risk. In particular, the high uncertainty about climate change makes it more likely to be a global catastrophic risk and more likely to be a large global catastrophic risk. Additionally, a comparison to nuclear winter shows that much of the uncertainty about climate change as a global catastrophic risk comes from complex systems interaction in more moderate climate change scenarios. The article finds that, based on the body of evidence currently available, climate change should indeed be considered to be a global catastrophic risk. Implications for the general study of global catastrophic risk are also presented.

Keywords: climate change, global catastrophic risk, risk, uncertainty

1. Introduction

Public discourse abounds with concern about catastrophic climate change. "The long-feared era of disastrous climate change has arrived", write Colman and Mathiesen (2021) in regards to the latest report of the Intergovernmental Panel on Climate Change (IPCC), a report described as a "code red for humanity" by United Nations Secretary-General António Guterres (United Nations 2021). A prior IPCC report generated headlines such as "We have 12 years to limit climate change catastrophe, warns UN" (Watts 2018). There is even a sizable Wikipedia article on "climate apocalypse", described as "a predicted scenario involving the global collapse of human civilization and potential human extinction as either a direct or indirect result of anthropogenic climate change".[1]

Academic research has expressed similar concern. Schelling (1992, p.8) framed climate change policy as a matter of "insurance against catastrophes". Weitzman (2009, p.1) worried that "the probability of a disastrous collapse of planetary welfare is nonnegligible". Lenton et al. (2019, p.592) warn of tipping points in the global climate system that "are looking more likely" to be crossed, with effects that "would be catastrophic". Bradshaw et al. (2021, p.1) implicate climate change in bringing about a "ghastly future" characterized by great "threats to the biosphere and all its lifeforms—including humanity".

This concern is not universally shared. There has long been an aggressive campaign to sow doubt about the science of climate change and the seriousness of the issue (Oreskes and Conway 2010). Some of it is absurd, such as the recent claim spreading on social media that "NASA admitted that man-made climate change is a hoax" (Reuters Staff 2021). Other work is more subtle, such as the argument of Cass (2017) that the effects of climate change will be tolerable and that the real problem is draconian

[1] https://en.wikipedia.org/wiki/Climate_apocalypse

efforts to address climate change, including via "the trampling of democratic norms".

Within academic research, consensus about catastrophic climate change has not been universal. Nordhaus (2012, p.217), using an approach similar to that of Weitzman (2009), found that "Perhaps climate change is not a Dismal [i.e., catastrophic] event for the globe, or even for countries". In an edited collection on catastrophic risk, a chapter on climate change describes it as "tough, but endurable" (Frame and Allen 2008, p.282). Bostrom (2019, p.460) imagines the implications of a hypothetical scenario dubbed "worse global warming", described as "a prospect with far greater civilization-destroying potential than the actual expectation", implying that actual global warming scenario is not a significant threat.

Despite the considerable interest in catastrophic climate change and the enormous body of research on the general topic of climate change, relatively little research has studied the risk of catastrophic climate change. The overall climate change literature has paid relatively little attention to warmer and more catastrophic scenarios, and has paid disproportionately little attention given the probability of these scenarios (Brysse et al. 2013; Jehn et al. 2021). Research on the economics of climate change has often emphasized catastrophic risk, but this literature is focused on quantifying the social cost of carbon and lacks detailed treatment of how climate change might cause global catastrophe (Weitzman 2009; Wagner and Weitzman 2016). Similar lack of detail is found in the bibliometric analysis of Butler (2018). One more detailed treatment is provided by Lynas (2020).

Some limited additional contributions have come from the field of global catastrophic risk (GCR). This field is specifically focused on large-scale threats to humanity. Climate change is often taken to be among the GCRs, though until recently, analysis of climate change as a GCR has been limited. Early studies such as Rees (2003), Posner (2004), and Frame and Allen (2008) lack detail especially on the potential for catastrophic effects on the human population. More detail is found in recent studies by Ord (2020), Beard et al. (2021), and Kemp et al. (2022); these studies all find that climate change has potential to be a GCR, but they emphasize the high uncertainty and the need for further research.

Given the complexity of the topic and the lack of prior research, it can be concluded that the uncertainty about catastrophic climate change is indeed high. What should one make of this? Should climate change be considered to be a global catastrophic risk (GCR)? If so, should climate change be considered to be a GCR of any significance?[2] These are the central questions to be explored in this article.

The article advances the study of catastrophic climate change by relating existing knowledge of climate change to the underlying theory of GCR. The article shows that the high uncertainty makes it more likely that climate change should be considered to be a GCR, and a significant GCR at that. The article additionally shows that, contrary to some prior discussion, the basis for considering climate change to be a GCR is not unusually weak or speculative; this is demonstrated via comparison to another recognized GCR, nuclear winter. Finally, the work presented here makes some general contributions to the theory of GCR.[3]

2. Definitions

Before addressing the question of climate change and GCR, the definitions of the terms "climate change" and "global catastrophic risk" both merit attention.

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2 The usage of "be considered to be" recognizes that the status of climate change as a GCR ultimately comes down to subjective judgments in consideration of the available evidence, as in subjective or Bayesian probability theory. Because a global catastrophe would be unprecedented, the risk of it cannot be evaluated with statistical techniques.

3 For related literature on the theory of GCR, see Avin et al. (2018), Liu et al. (2018), Beard et al. (2020) and Baum (2020).

2.1 Climate Change

In common usage, the term "climate change" refers to the anthropogenic global warming that is driven mainly (but not exclusively) by greenhouse gas emissions from burning fossil fuels. This is usage of the term is found, for example, in the name *Intergovernmental Panel on Climate Change*. However, it is important to recognize that anthropogenic global warming is not the only type of climate change. Three other types of climate change are notable:

(1) Gradual natural climate change. This includes the glacial-interglacial cycles that occur with frequencies of approximately 23,000, 41,000, and 100,000 years (Archer 2008; Haqq-Misra 2014) as well as the gradual warming and expanding of the Sun, which gradually warms Earth and will render Earth uninhabitable in hundreds of millions to billions of years (O'Malley-James et al., 2014; Wolf and Toon, 2015). Gradual natural climate change is less of an imminent threat but may be catastrophic for the long-term trajectory of human civilization (Baum et al. 2019).

(2) Rapid cooling events. These events involve rapid accumulation of particles in the atmosphere, which block incoming sunlight, causing the surface of Earth to cool. The primary drivers are sufficiently large nuclear war, volcano eruption, and asteroid/comet collision. The result is a "winter" or "autumn" event that may severely threaten humans and other species, such as by reducing plant growth and therefore reducing the food supply (Driscoll et al. 2012; Xia and Robock 2013; Toon et al. 2016; Coupe et al. 2019). These events pose a significant and immediate/ongoing threat to human civilization.

(3) Rapid warming events. These events occur following the rapid removal of something that had been lowering global surface temperatures.[4] This includes the rapid cooling events described above. The particles that enter the atmosphere tend to fall out within weeks (for particles in the troposphere) to years (for particles in the stratosphere) (Coupe et al. 2019). Additionally, it includes events involving the abrupt cessation of geoengineering, such as when particles are intentionally injected into the stratosphere to counteract anthropogenic global warming, and then the injections are halted. Following a nuclear/volcanic/asteroid/comet winter, rapid warming may be a welcome occurrence that restores more hospitable conditions. Following a geoengineering cessation event, rapid warming can be catastrophic, forcing rapid adaptation to elevated temperatures (Baum et al. 2013; Tang and Kemp 2021). This is an important type of potential indirect effect of anthropogenic global warming.

All three of these other types of climate change are important for GCR. Therefore, it is important for discussions of climate change and GCR to clarify which type(s) of climate change are under consideration. To maintain consistency with the common usage, this article uses "climate change" to refer exclusively to anthropogenic global warming.

Discussions of climate change vary in terms of the time frames that they focus on. The year 2100 is a common end point in climate change research.[5] However, climate change does not stop at 2100; indeed, it is likely to be worse after then if atmospheric greenhouse gasses continue to accumulate. This paper is interested in global catastrophes that could occur at any time; its arguments apply to times both before and after 2100.

2.2 Global Catastrophic Risk

GCR is the possibility of global catastrophe. The concept of global catastrophe can be defined in a variety of ways.

Existing definitions include events that cause at least millions of deaths or tens of billions of

[4] It has been proposed that there can also be rapid warming as part of anthropogenic global warming, such as via the release of greenhouse gasses from the thawing of permafrost. See for example Schuur et al. (2015), finding it unlikely that permafrost thaw would cause rapid warming.

[5] For example, Kemp et al. (2022, p.5) define extreme climate change as "Mean global surface temperature rise of 3°C or more above preindustrial levels by 2100". Note that other parts of Kemp et al. (2022) consider longer time scales.

dollars of damage (Bostrom and Ćirković 2008), the death of 10% (Cotton-Barratt et al. 2016) or 25% of the global human population (Morrison 1992), one billion deaths (NRC 2010), a “significant reduction in humanity’s ability to survive in its current form”, especially via breakdown of critical systems (Avin et al. 2018, p.21), and a large and damaging change to the state of the global human system (Baum and Handoh 2014).

Definitions of GCR play an important role in the recent literature on climate change and GCR. Ord (2020) uses the term “existential risk” instead of GCR; for present purposes, these two terms can be used interchangeably. Ord (2020, p.44) defines existential catastrophe as “the destruction of humanity’s longterm potential”, with humanity’s longterm potential being “the set of all possible futures that remain open to us”, and “any reduction in humanity’s potential should be understood as permanent”. This is an unreasonably extreme definition. Under this definition, for something to be an existential risk, it would need to be able to destroy humanity’s long-term potential *under all possible scenarios* (i.e., the set of all possible futures). An event that leaves some tiny, infinitesimal possibility of humanity achieving its long-term potential would, under this definition, not constitute an existential catastrophe. As discussed below, this extreme definition has important implications for the evaluation of climate change risk.[6]

Beard et al. (2021, p.2) use a multifaceted definition of GCR. An event would be a global catastrophe if it results in a large and sudden population decline, civilization collapse, and/or a permanent reduction in humanity’s potential. The “humanity’s potential” criterion poses the same problems as the Ord (2020) definition, but the other two criteria are reasonable. Additionally, Beard et al. (2021, p.3) also state that “To present a credible risk of producing a global catastrophe, any change would need to be at least one of the following:

- So profound that adaptation is impossible;
- So rapid that adaptation is unfeasible;
- So complex that the level of coordination needed to adapt to it is unachievable;
- Able to work against our efforts to adapt to it, or to adapt itself to us”.

The first three of these criteria raise the same problem as the Ord (2020) definition: as long as there is some tiny probability that adaptation is possible or feasible or that coordination is achievable, then a risk is not a “credible” GCR. The fourth criterion is ambiguous.

Finally, Kemp et al. (2022, p.5) define GCR as “the probability of a loss of 25% of the global population and the severe disruption of global critical systems (such as food) within a given timeframe (years or decades).” This definition does not raise the same problems as the definitions of Ord (2020) and Beard et al. (2021).

3. Uncertainty Strengthens the Case for Climate Change as a Global Catastrophic Risk

For any particular definition of GCR, it is not known whether climate change will cause global catastrophe. The matter is highly uncertain. Further research could help, though there may be limits to how much the uncertainty can be reduced given the complex and unprecedented nature of human-environment interactions in a warming world. This section shows that, in contrast with some prior literature (specified below), the high uncertainty means that climate change is more likely to pose a GCR, and a larger one at that.

3.1 Uncertainty and the Global Catastrophe Threshold

Across the various definitions of GCR, an essential aspect is that they all involve some minimum threshold of severity. All possible events that exceed this severity threshold are global catastrophes. Definitions of GCR vary in terms of where they set the threshold. The threshold may be the death of

[6] Ord (2020) also considers that climate change might not cause existential catastrophe on its own, but instead might be a contributing factor in a multifaceted existential catastrophe scenario, though this possibility is not analyzed in detail.

some fraction of the global human population, or some type of disruption to global human civilization or its future potential, etc.

Let S_T be the severity threshold for some definition of GCR. A possible event X is a GCR if there is some nonzero probability that the severity S of X exceeds S_T, i.e. if there is a nonzero probability that $S(X)>S_T$. In general, the exact severity of X is uncertain: given available information, a range of severities are possible. Let f(S(X)) be the probability density function of S(X), in which the value of f(S(X)=V) indicates the relative likelihood that X has severity V.[7]

Suppose S(X) has finite upper and lower bounds S_{max} and S_{min}, outside of which f(S(X))=0. For bounded distributions, define the size of uncertainty as $Z_b=S_{max}–S_{min}$. In general, a possible event with larger uncertainty Z_b is more likely to be a GCR. Larger Z_b can come exclusively from smaller S_{min}, but if S_{max} is larger, then it is more likely that $S_{max}>S_T$. Therefore, larger uncertainty tends to make it more likely that a risk with a bounded severity distribution is a GCR.

Alternatively, suppose S(X) is unbounded, such as in a normal distribution and many other probability distributions. In any unbounded distribution, $S_{max}=\infty$ and therefore X is a GCR. However, X may only be a GCR in a trivial sense, with some tiny probability of $S(X)>S_T$ that is insignificant for practical (e.g., policy) purposes.[8] Let $P_T(X)$ be the probability that $S(X)>S_T$. Let P_{min} be the minimum value of P_T for X to be considered a nontrivial GCR. In other words, X is a nontrivial GCR if $P_T(X)\geq P_{min}$. For unbounded distributions, define the size of the uncertainty Z_{ub} as the standard deviation of S(X). There is no underlying theoretical reason to favor the standard deviation over other measures of the "width" of a distribution, but it nonetheless suffices for present purposes. In general, a possible event with larger uncertainty Z_{ub} is more likely to be a nontrivial GCR. Larger Z_{ub} can come exclusively from more variation in smaller severities, as in a distribution with a fat left tail and thin right tail, but if there is more variation in larger severities, then it is more likely that $P(X)\geq P_{min}$. Therefore, larger uncertainty makes it more likely that a risk with an unbounded severity distribution is a nontrivial GCR.

Figure 1 illustrates this theoretical point. Figures 1a and 1b show risks with greater uncertainty about the severity of the impacts. Figures 1c and 1d show risks with less uncertainty about the severity of the impacts. Figures 1a and 1c show risks that are smaller as measured by the expected value of severity. Figures 1b and 1d show risks that are larger as measured by the expected value of severity. The vertical line across each graph indicates the global catastrophe threshold. Clearly, the more uncertain risks are more likely have some nonzero or nontrivial probability of exceeding the threshold. In other words, the more uncertain the severity of a risk is, the more likely the risk is to be a GCR or a nontrivial GCR. There is a sense in which this places the burden of proof on demonstrating that something is *not* a GCR or *not* a nontrivial GCR: a risk should be considered to be a GCR until it can be determined that the severity of the risk cannot exceed the global catastrophe threshold, and it should be considered a nontrivial GCR until it can be determined that the severity can only exceed the global catastrophe threshold in trivially rare scenarios. Indeed, the top graphs of Figure 1 can be interpreted as initial probability distributions for the severity of a risk, with the bottom graphs being updated probability distributions after new information is learned so as to reduce uncertainty about the risk.

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7 Here it is assumed that it is possible to draw probability distributions for the risk under consideration. For some theories of uncertainty, when uncertainty is sufficiently high, probability distributions cannot be drawn (Bevan 2022).

8 In policymaking, it is common to ignore tiny probabilities, though when the severity is sufficiently high, it can be argued that even tiny probabilities should be considered (Adler 2007). It can even be argued that highly speculative and unlikely catastrophic risks merit some serious attention (Ćirković 2012). However, given the existence of multiple GCRs with more substantial probabilities, it may be appropriate to ignore GCRs whose probabilities are many orders of magnitude lower.

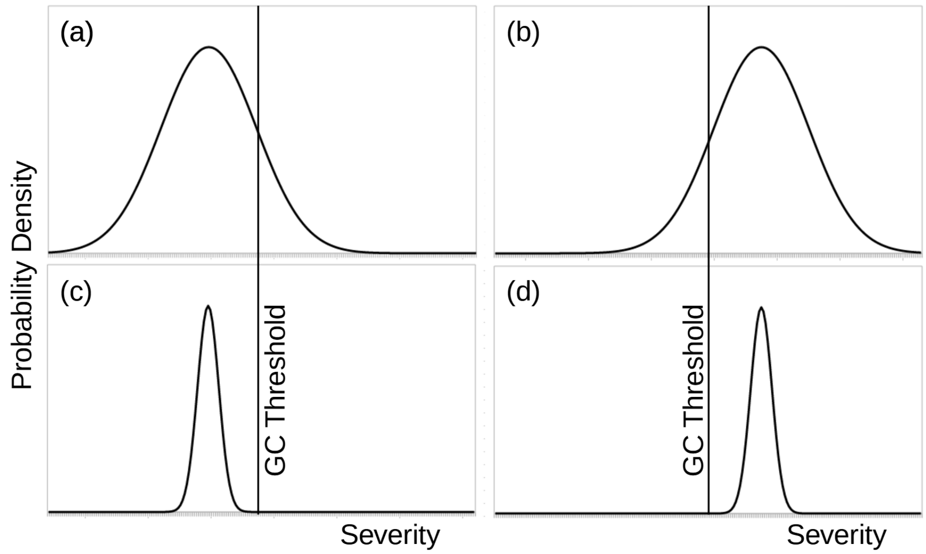

Figure 1. Four probability distributions of the severity of catastrophes near the global catastrophe threshold.

3.2 Uncertainty and Climate Change

Prior studies of climate change and GCR may not explicitly reject the reasoning outlined in Section 3.1, but some of them present ideas that run counter to this reasoning.

The Ord (2020) definition of existential catastrophe resolves some forms of uncertainty in favor of a risk not being an existential risk. Specifically, if there is uncertainty about how severe an event would be, it is less likely to be an existential risk. More precisely, if there is some chance that an event might not destroy humanity's long-term potential, then it is not an existential risk. In other words, any uncertainty about whether something would destroy humanity's long-term potential means that it is not an existential risk.

The Beard et al. (2021) definition is similar, in particular via the first three criteria listed in Section 2.2. These criteria resolve uncertainty in favor of a risk not being a GCR. If there is uncertainty about whether adaptation is possible or feasible or if coordination is achievable, then these criteria are not met such that the risk might not be a GCR. In other words, if there is some chance, however infinitesimal, that adaptation might be possible or feasible or coordination achievable, then the risk might not be a GCR.

To see the implications of these definitions, consider scenarios in which extreme warming creates, in some parts of the Earth at some times, heat stress that exceeds what the human body can tolerate (Sherwood and Huber 2010). Ord (2020) observes that even in a very extreme 20°C warming scenario, the Sherwood and Huber (2010) analysis finds that it would be thermally possible for humans to survive in certain coastal and high-altitude locations. Ord (2020, p.114) describes this as "an unparalleled human and environmental tragedy" but that "it is hard to see how any realistic level of heat stress could pose such a risk [of existential catastrophe]".

It does indeed seem correct that, given the evidence currently available, humanity might be able to endure the heat stress of 20°C warming and still go on to achieve at least a portion of its long-term potential. Perhaps humans would survive in the coastal and high-altitude regions that Sherwood and Huber (2010) identify as having more moderate temperatures. Or, perhaps humans would survive indoors in "air-conditioned techno-domes" that maintain safe temperatures for human populations and their agriculture (Lynas 2020, p.215). Perhaps this would be enough for the human population to persist for however many generations it takes for global temperatures to cool off, or until biological humans are supplanted by heat-resistant AI, or some other potential-realizing outcome. Thus, Ord (2020) would appear correct in the claim that 20°C heat stress does not destroy humanity's long-term potential across all scenarios. Likewise, 20°C heat stress probably does not meet the Beard et al. (2021) criteria of adaptation being impossible or unfeasible or coordination unachievable.

However, it is entirely plausible that in some scenarios, 20°C heat stress would cause a global or existential catastrophe defined as a large and sudden population decline, the collapse of civilization, and/or the destruction of humanity's long-term potential. This is especially plausible when also accounting for the other effects of climate change. For example, the areas with tolerable temperatures may turn out to be inadequate for agriculture, such as due to changes in weather patterns and sea level, adverse topography, and poor soil. Lynas (2020, p.219-225) surveys the geography of habitability under just 5°C of warming, finding only limited options available. The options at 20°C would be even fewer. Even if there is a viable way to survive, it is plausible that humans would fail to do so. If one is specifically concerned about the human population, civilization, and its long-term potential, 20°C of warming is clearly an outcome to avoid. It may also be important to avoid much lower amounts of warming, as others have suggested.[9] It follows that the Ord (2020) and Beard et al. (2021) definitions should not be used for evaluating GCR or existential risk due to how they handle uncertainty about the severity of extreme events.

Some prior literature on catastrophic climate change has offered perspective similar to what is illustrated in Figure 1. The literature has highlighted the uncertainty about the human impacts of climate change, the implications of the uncertainty for treating climate change as a catastrophic risk, and the implications for policy, in particular by adding urgency and importance to policy for addressing climate change. Here are two examples from the literature.

First, in what may be the first articulation of this point in the climate change literature, Schelling (1992) states, "there isn't any scientific principle according to which all alarming possibilities prove to be benign upon further investigation… Insurance against catastrophes is thus an argument for doing something expensive about greenhouse emission" (p.8). This line is saying that (1) given the state of knowledge available circa 1992, the possibility of catastrophic climate change could not be ruled out, (2) there is no reason to assume that future research necessarily would rule out the possibility of catastrophic climate change, and (3) the fact that the possibility of catastrophic climate chance cannot be ruled out constitutes a reason for aggressive action to reduce greenhouse gases. In essence, the lingering uncertainty means that climate change should be treated as a catastrophic risk and responded to accordingly.

Second, in a particularly influential treatment of catastrophic climate change, Weitzman (2009) states, "The climate science seems to be saying that the probability of a disastrous collapse of planetary welfare is nonnegligible, even if this tiny probability is not objectively knowable" (p.1)… "For situations where there do not exist prior limits on damages (like climate change from greenhouse warming), CBA is likely to be dominated by considerations and concepts related more to catastrophe insurance than to the consumption smoothing consequences of long-term discounting—even at empirically plausible interest rates" (p.2). This line is saying that (1) uncertainty about the impacts of climate change are such that there is no clear limit on their severity, (2) cost-benefit analysis should account for the possibility of catastrophe, even though its probability cannot be rigorously quantified, and (3) the possibility of catastrophe is likely to be the dominant factor in climate change cost-benefit analysis.[10] In essence, the high uncertainty about extreme damages results in placing significant weight

[9] "In my view, worldwide food shortages are the most likely trigger of large-scale civilisational collapse in a three-degree world" (Lynas 2020, p.142); "at four degrees a full-scale global collapse of human societies is probable" (p.ix); but also human extinction "is unlikely even with the catastrophic heat-related impacts expected in the five-degree world" (p.219). Wagner and Weitzman (2015, p.88) find warming over 6°C to be "an indisputable global catastrophe".

[10] The mention of interest rates references the heated debate among climate economists of how to discount future consumption and welfare within climate change cost-benefit analysis (e.g., Nordhaus 2007; Stern 2008). Additionally,

on the possibility of catastrophe within the cost-benefit analysis.

Analysis of catastrophic climate change is often flawed. A major problem is the common usage of utility functions that posit that, at zero consumption, total utility is negative infinity (when it should be zero); see for example Weitzman (2009, Equation 1).[11] Nonetheless, the work (e.g., Schelling 1992; Weitzman 2009) makes important points: extreme catastrophic risk is very important in policy terms, it should not be ignored just because the uncertainty is high, and indeed the uncertainty makes the catastrophic risk more significant, not less.

The catastrophic climate change literature has been especially helpful as a counterpoint to tendencies by climate scientists to emphasize more moderate scenarios in which the scientific basis is more robust and conclusions are less dramatic (Brysse et al. 2013; Jehn et al. 2021).[12] In general, scientists often gravitate toward phenomena that are more readily characterized and away from more opaque phenomena, even if the opaque phenomena are very important. Baum et al. (2019, p.53) liken this to "the drunk searching for his keys under the streetlight: it may be where empirical study is more robust, but the important part lies elsewhere". The catastrophic climate change literature has been a constructive force for shifting attention and emphasis. For example, Schneider (2009) describes the tendency of the Intergovernmental Panel on Climate Change to focus on more moderate and likely climate change scenarios, and references analysts such as Weitzman in calling for greater emphasis on catastrophic risk.

The catastrophic climate change literature also underscores the importance of research to address the uncertainty:

> "But to pay a couple percent of GNP as insurance premium, one would hope to know more about the risk to be averted. I believe research to improve climate predictions should be concentrated on the extreme possibilities, not on modest improvements to median projections" (Schelling 1992, p.8).

> "A clear implication of this paper is that greater research effort is relatively ineffectual when targeted at estimating central tendencies of what we already know relatively well about the economics of climate change in the more plausible scenarios. A much more fruitful goal of research might be to aim at understanding even slightly better the deep uncertainty (which potentially permeates the economic analysis) concerning the less plausible scenarios located in the bad fat tail. I also believe that an important complementary research agenda, which stems naturally from the analysis of this paper, is the desperate need to comprehend much better all of the options for dealing with high-impact climate-change extremes." (Weitzman 2009, p.17).

These comments are very much in the spirit of Beard et al. (2021) and Kemp et al. (2022), whose core projects are to clarify the ways in which climate change could cause global catastrophe and how that could be avoided.

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whether the possibility of catastrophe is indeed the dominant factor depends on whether the distribution of possible damages is "thin-tailed" or "fat-tailed". For brevity, this paper will not elaborate on "tail fatness", but see e.g. Weitzman (2009) for discussion.

11 What this means is that when an individual or a society consumes zero dollars of goods and services, Weitzman (2009, Equation 1) treats that individual or society as having a welfare of negative infinity, which is to say their life/lives are going infinitely horribly. In fact, when consumption is zero, the individual or society is probably dead, in which case their welfare is zero.

12 More moderate scenarios may be more probable, but they have been found to receive research attention out of proportion with their estimated probability. In other words, given the probability of more extreme scenarios, they should be getting more research attention (Jehn et al. 2021).

4. Climate Change and Nuclear Winter Have Comparable Mechanisms for Global Catastrophe

A comparison between climate change and nuclear winter provides further insight on the status of climate change as a GCR as well as the general relation between uncertainty and GCR. Two interrelated issues are addressed in this section: (1) the significance of identifying mechanisms for how a possible event could cause global catastrophe and (2) the different uncertainties in moderate vs. extreme events. Beard et al. (2021) proposes that climate change lacks "clear and credible mechanisms" for causing global catastrophe, whereas nuclear winter does not. Closer inspection finds this to be incorrect; this strengthens the case for climate change as a GCR. For both risks, the mechanisms are clearer and more credible in more extreme scenarios. An understanding of the mechanisms is important for reducing uncertainty about climate change risk; it can be of further value for informing actions that reduce the risk by addressing the mechanisms.

4.1 Nuclear Winter

To set the stage for its discussion of climate change, Beard et al. (2021) briefly discuss the risk of nuclear winter. Beard et al. (2021, p.2) specifically references Sagan (1983a) as an influential study that sets out "a clear and credible mechanism by which nuclear war might lead to global catastrophe by triggering a nuclear winter". Sagan (1983a) was indeed influential, though it it was also published as a commentary article published in *Foreign Affairs*, a policy magazine. Therefore, it is a good example of how to draw attention to a research idea, but it is arguably not a good example of robust scientific research on GCR. For clarity on the status of nuclear winter as a GCR, it is essential to dig deeper.

Sagan (1983a) draws heavily on Turco et al. (1983), an environmental modeling study published in *Science*. This work was controversial at the time because it was initially released in the popular magazine *Parade* (Sagan 1983b; for discussion of the controversy, see Badash 2009). Turco et al. (1983) used only a one-dimensional radiation model. Subsequent work using three-dimensional models found significantly lower cooling (Schneider and Thompson 1988). Indeed, the term "nuclear winter" was based on Turco et al. (1983) finding temperature decreases of up to 35°C in mid-latitudes, sufficient to cause winter temperatures during summer. Later studies found cooling of up to around 10°C, and likewise proposed the term "nuclear autumn" as a more precise characterization (Schneider and Thompson 1988). The latest modeling continues to find temperature decreases of around 10°C (Coupe et al. 2019).

The above concerns temperature declines. However, as shown in Section 2.2, GCR is generally defined in terms of human impacts, not environmental changes. A primary mechanism for human consequences from nuclear winter (or "autumn") is famine via crop failure induced by the cooling. Sagan (1983a) infers the human consequences without any methodologically rigorous analysis. Indeed, the connection between cooling and agriculture devastation is based not on peer-reviewed research but on a private communication with two people (Sagan 1983a, footnote 16). More recently, the agricultural effects of nuclear winter have been studied using sophisticated crop models (e.g., Xia and Robock 2013), though these studies concentrate on more moderate scenarios than Sagan (1983a). Other societal effects, such as on economic and political activity, have not been studied to any significant extent.

Furthermore, nuclear winter would not rate as a credible GCR according to the first three of the four Beard et al. (2021) criteria presented in Section 2.2. Even a cooling of 35°C may not produce conditions so severe that adaptation would be impossible or unfeasible or coordination unachievable. The minimum temperature needed for the survival of the human body could be achieved via indoor heating, as is already done every winter around the world. Food shortages could be met via food stockpiles and "alternative foods" grown via sources of energy other than the Sun (Baum et al. 2015). Other stressors may also be manageable, especially given adequate preparation. Indeed, Ord (2020), using a similarly restrictive definition of existential risk as discussed above, expresses skepticism about nuclear winter as an existential risk similar to the skepticism expressed about climate change, though Ord ultimately finds nuclear winter to also be an existential risk.[13]

4.2 Climate Change

In contrast with its brief discussion of nuclear winter, Beard et al. (2021, p.2) finds that "despite the well-developed consensus on the science of climate change… there remains no clear and credible mechanism for how a changing climate could cause global catastrophes". This is arguably incorrect; heat stress may constitute one such mechanism as discussed above. Indeed, drawing on the heat stress study of Sherwood and Huber (2010), Beard et al. (2021) finds that climate change could bring temperature increases large enough to exceed "widely accepted limits to humanity's ability to survive the direct effects of climate change" (p.2). Beard et al. (2021) notes that such large temperature increases "would require either that high levels of greenhouse gas (GHG) emissions continue far into the future or that natural feedback mechanisms are far stronger than expected" (p.2). However, Beard et al. (2021) does not rule out the possibilities of high levels of emissions or strong feedback mechanisms. The heat stress limit is therefore comparable to extreme nuclear winter: both occur in extreme scenarios (large amounts of global warming or large nuclear wars) and both are survivable only via careful adaptations, such as air conditioning to avoid dying from heat stress or indoor heating to avoid dying from extreme cold.

There is a more general point to be made here about the relationship between uncertainty, GCR, and moderate vs. extreme scenarios. Most of the discussion in Beard et al. (2021) focuses on climate change scenarios involving more moderate amounts of warming. It is indeed true that in these moderate scenarios, the prospect of global catastrophe is more ambiguous. For moderate warming to cause global catastrophe, some complex chain of events may be necessary. Beard et al. (2021) describes several such chains, involving interconnections between climate change and (for example) food security, violent conflict, infectious diseases, and geoengineering; Lynas (2020) and Kemp et al. (2022) further elaborate on these sorts of factors. Because these scenarios are both complex and largely or completely unprecedented, there is a high degree of uncertainty about them. Nonetheless, they do provide clear mechanisms for moderate warming to result in global catastrophe. Whether these mechanisms are also "credible" may depend on subjective standards of credibility.

The above discussion also applies to moderate nuclear winter scenarios. Early research by Sagan (1983a) and Turco et al. (1983) focused on extreme scenarios of large-scale US-USSR nuclear war with thousands of nuclear explosions. More recent research has focused on more moderate scenarios of India-Pakistan nuclear war with just tens of nuclear explosions (e.g., Toon et al. 2007). Such scenarios still have significant declines in agricultural output (Xia and Robock 2013), but not to the point of being unsurvivable for the total human population. Whether such scenarios would result in global catastrophe may depend on the same sorts of complex interconnections as with moderate climate change, such as in the Helfand (2013) proposal that the famine from moderate nuclear winter may induce infectious disease epidemics.

The ideas of this section can be summarized as follows. For many catastrophic risks, extreme forms of the risk have clear and credible mechanisms for exceeding the threshold of global catastrophe. Even then, adaptation may still be possible, such that there is no certainty that global catastrophe will occur. This includes extreme cooling in nuclear winter (winter temperatures in summer, precluding normal agriculture) and extreme warming in climate change (past the physiological heat stress tolerance of human bodies). For more moderate forms of the risk, in which human impacts may be near the global

[13] Ord (2020, p.102) writes that "I am inclined to believe that the central nuclear winter scenario is not an existential catastrophe", because some people could survive in a few locations such as New Zealand and parts of Australia, and may even retain technology and institutions. The fact that much of the technology is dependent on global supply chains is not considered.

catastrophe threshold, there may still be clear mechanisms, though these might or might not be “credible”. In these moderate scenarios, the GCR may depend on complex and uncertain chains of events. This includes moderate scenarios for both nuclear winter and climate change.

5. Conclusion

This article seeks to address the status of climate change—defined as anthropogenic global warming—as a GCR. It is widely recognized that climate change is occurring, is steadily becoming more severe, and that it can have significant harmful effects for human populations around the world. There is also high uncertainty about how severe the harms would be. The question is whether those harms could be severe enough to be a global catastrophe.

Section 3 shows that a risk should be considered to be a GCR unless and until it can be established that the global catastrophe threshold would not be exceeded if that type of event occurs. Furthermore, a risk should be considered to be a nontrivial GCR, with more than just some tiny, negligible probability of causing global catastrophe, unless and until it can be established that the global catastrophe threshold would only be exceeded in rare, trivial cases. A risk with high uncertainty is more likely to pose a GCR; it is also more likely to pose a nontrivial GCR in the sense of having some nontrivial probability of resulting in global catastrophe. For climate change, the available body of evidence is limited and the uncertainty is high, making it difficult to rule out the possibility of climate change causing global catastrophe.

Section 4 shows that more moderate events may have higher uncertainty about the possibility of the event causing global catastrophe. Extreme climate change and extreme nuclear winter have relatively straightforward mechanisms for causing global catastrophe. Moderate scenarios may only cause global catastrophe via complex and uncertain cascading effects such as violent conflict and infectious disease. Moderate climate change scenarios may be more probable, but some more extreme scenarios cannot be ruled out.

From this analysis, it can be concluded that, given current knowledge, climate change should be considered to be a GCR. Future research could reduce the uncertainty about climate change, potentially finding that climate change should not be considered to be a GCR. That would be good news! Alternatively, future research could bring bad news, in particular that climate change is an even more significant GCR than current knowledge indicates. Unless and until future research rules out the possibility of global catastrophe from climate change, climate change should be considered to be a GCR.

This raises the question of how large of a GCR climate change is. Recall from Section 2.2 that a risk with an unbounded severity probability distribution should be considered to be a nontrivial GCR until it can be demonstrated that the severity only exceeds the global catastrophe threshold in trivially rare scenarios. Can this be demonstrated? The most detailed studies of climate change and GCR (Ord 2020; Beard et al. 2021; Kemp et al. 2022) all find that climate change at least has potential to be a GCR. These studies do not rule out the possibility of climate change as a nontrivial GCR, and they may be understating the risk for reasons explained in this article. Furthermore, other work has argued that climate change is a large GCR (Lynas 2020), perhaps even the largest GCR (Wagner and Weitzman 2015, p.83-90). It would therefore seem to follow that, for now, climate change should be considered to be a nontrivial GCR.

The exact size of GCR from climate change is beyond the scope of this article. Likewise, this article’s comparison between climate change and nuclear winter finds that both are similar in their status as GCRs; this does not mean that both risks are of similar size as measured in terms of probability times severity. Two risks can have equal claim to being GCRs despite being of very different sizes. This follows from the definition of GCR as a risk of an event that, if it occurs, the severity would have some nonzero probability of exceeding the global catastrophe threshold. This point holds across the range of existing definitions of the global catastrophe threshold.

The comparison between climate change and nuclear winter points to a more general insight. Many GCRs involve sets of scenarios of varying severity. The more severe scenarios are harder to adapt to, but not necessarily impossible to adapt to. Absent rigorous adaptation, global catastrophe would be highly likely. The more moderate scenarios involve a wider distribution of possible severities, with global catastrophe potentially involving complex and chains of events. Whether the moderate scenarios would result in global catastrophe is highly uncertain. This applies to climate change, nuclear winter, pandemics, volcano eruptions, asteroid and comet collisions, and more. The primary examples of GCRs that are *not* characterized in this way are those in which the complete destruction of life on Earth is unavoidable, such as in high energy physics disasters or runaway artificial intelligence. The complexities of moderate scenarios demand research attention. This includes, but is not limited to, moderate climate change scenarios.

Another important issue not covered in this article, but addressed in Liu et al. (2018) and Kuhlemann (2019), is the slow dynamics of climate change. Greenhouse gas emissions accumulate gradually in the atmosphere, causing gradual changes to climate and in turn to human society. Gradual change may be easier to adapt to, making climate change less of a GCR. Alternatively, there may be less motivation to adapt to gradual climate change, as in the metaphor of the boiling frog,[14] making climate change more of a GCR. Furthermore, climate change has a relatively long duration, with effects persisting for centuries or even longer. In contrast, in events such as nuclear winter, an initial abrupt disruption is followed relatively quickly by a return to normal conditions. The long duration of climate change could have adverse long-term implications for human populations.

Furthermore, gradual climate change and its accompanying effects on human populations may in turn affect other GCRs. It may be productive to think of climate change less as a GCR on its own and more as a factor in GCR. Untangling these cross-risk interconnections is another worthy focus of future research. Beard et al. (2021) and Kemp et al. (2022) describe potential interconnections in some detail and suggest specific research directions.

For practical decision-making purposes, further research is not always needed. For example, the case for reducing greenhouse gas emissions does not depend on whether climate change would cause global catastrophe. An aggressive emissions reduction program is worth pursuing to avoid more moderate damages from climate change and often to realize the co-benefits of emissions reduction, such as via local health benefits from reduced air pollution (Creutzig et al. 2021).

Nonetheless, there are some decisions that would greatly benefit from further research. For example, should society pursue dangerous technologies that could greatly help avoid catastrophic climate change but that could also pose other GCRs? Examples of such technologies include stratospheric geoengineering, molecular nanotechnology, and artificial general intelligence (Baum 2014; Umbrello and Baum 2018). The more likely climate change is to cause global catastrophe, the more worthwhile it may be to pursue these technologies.

Given the incredibly high stakes, it can be vital for decision-making about GCR to be well-informed. At the same time, it is important to recognize that good information about the GCRs is often unavailable. The GCRs are too complex, unprecedented, and overall uncertain. In the face of such uncertainty, it is important to select wide probability distributions and proceed accordingly.

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[14] The idea is that a frog that is placed in boiling water jumps right back out, whereas a frog placed in mild water that is then gradually boiled stays in and dies. The latter part is now recognized as false: the frog jumps out. Nonetheless, it is used as a metaphor for the failure to adapt to gradually changing conditions.

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