Reflections on the Risk Analysis of Nuclear War

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Abstract
This paper presents reflections on the use of risk analysis for understanding and informing policy decisions about nuclear war. A quantitative evaluation of risk arguably should be central to many important nuclear weapons decisions, such as disarmament and launch alert status, because these decisions involve tradeoffs between different risks. However, nuclear war is a difficult risk to analyze, little effort has been made to analyze it, and nuclear war policy decisions have made little use of risk analysis. The paper demonstrates this via a detailed review of the nuclear war risk literature, a summary of a new model for nuclear war risk produced by the Global Catastrophic Risk Institute, and a discussion of the use of risk analysis in nuclear war decision-making. Despite the challenges, there are significant opportunities for progress on both the analysis and the decision-making. The paper finds that, at this time, the limiting factor is mainly the use of risk analysis for decision-making, such that people working on nuclear war risk should emphasize outreach to decision-makers. The paper's discussion is of relevance for guiding efforts to understand and reduce nuclear war risk, and is likewise applicable to many other risks, especially other global catastrophic risks.

1. Introduction

Consider this question: *Would the world be safer with or without nuclear weapons?* This is one of the most vital questions for the international community in its ongoing debate over nuclear disarmament. This is also a question for which a quantitative risk perspective is highly relevant. Unfortunately, the international community has not made much use of risk analysis in its discussion of this question, or of the numerous other important nuclear weapons policy questions for which risk analysis could also be highly relevant.

The aim of this paper is to reflect on the risk analysis of nuclear war, both in terms of its intellectual substance and its role in policy discussions and decisions. The paper draws on my own experience analyzing nuclear war risk and policy,[1] my experience in and observations of international policy discussions about nuclear war, as well as the broader literature and other discussions of the topic.

A few central points can be made. First, nuclear war is a difficult risk to analyze, because a nuclear war would be complex and largely unprecedented. Second, there has been little effort to analyze nuclear war risk, though the efforts to date have made some

[1] Se in particular Barrett et al. (2013), Baum (2015a; 2015b), Baum and Barrett (2018), and Baum et al. (2015; 2018).

meaningful progress. Third, nuclear war policy discussions have generally not sought input from risk analysis. These three points are interrelated, and they combine to paint a picture of a nuclear war policy debate that is not as well informed by risk analysis as it could be.

To illustrate this, let us revisit the question of whether the world would be safer with or without nuclear weapons. This is a key factor in the policy debate about nuclear disarmament. A large segment of the international community is concerned that the nuclear-armed states are not disarming rapidly enough. Their concern has translated into the new Treaty on the Prohibition of Nuclear Weapons. Meanwhile, other portions of the international community, primarily the nuclear-armed countries and their close allies, have argued against rapid nuclear disarmament.

Both sides of the debate are talking about risk, but they are talking about different aspects of risk. The rapid disarmament side argues that nuclear weapons increase the severity of conflict by emphasizing the large humanitarian consequences of nuclear weapons use (e.g., Fihn 2013). The non-rapid disarmament side argues that nuclear weapons decrease the frequency of major war by emphasizing nuclear deterrence (e.g., Mies 2012).[2] Both sides' arguments could be correct, but that would not resolve which side has the better disarmament policy.

A full risk analysis would consider the effect of nuclear weapons on both the frequency and the severity of war (or, more generally, on violent conflict). Figure 1 sketches what such a risk analysis might look like, assuming that nuclear weapons do indeed increase the severity and decrease the frequency of war. An important question is whether the decrease in frequency is enough to justify the increase in severity. If it is, then a case could be made for gradual disarmament or the permanent retention of nuclear weapons. Essentially, this would be to say that, in risk terms, the world would be safer with nuclear weapons than without.[3]

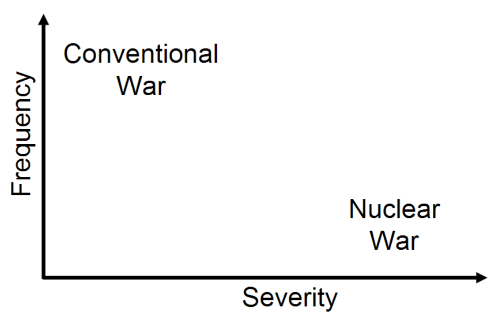

Figure 1. A possible sketch of the risk of major war with nuclear weapons (nuclear war) vs. without nuclear weapons (conventional war).

[2] The non-rapid disarmament side includes people arguing for gradual disarmament, no disarmament, and increased nuclear weapons proliferation, all of whom often base their arguments in the efficacy of nuclear deterrence.

[3] I briefly pursued a somewhat more detailed analysis of the risk of nuclear vs. non-nuclear war in Baum (2015c), concluding in favor of rapid disarmament, i.e. that the risk of non-nuclear war is smaller. My argument was based on the outsized severity of nuclear winter. However, at this time, I am not convinced that this analysis is correct. For example, it does not account for various prospects for the long-term trajectories of human civilization, a matter explored further in Baum et al. (2018b).

Risk need not be the only factor in nuclear disarmament policy. There can be other important factors, such as the cost of retaining or disarming nuclear weapons and the political preferences of various countries and other stakeholders. But risk would clearly seem to be an important factor. Risk analysis provides the means of answering the basic question of whether the world is safer with or without nuclear weapons. So we should expect to see significant demand from policy communities for risk analysis of both nuclear and conventional war. However, this has not been the case. Instead, policy communities have mostly just talked about aspects of the risk without any serious effort to analyze it.

It is important to note that the tradeoff shown in Figure 1 requires a quantitative risk analysis. The underlying question is whether nuclear weapons decrease the frequency of war more than they increase the severity. This is not a question that can be answered via qualitative characterization of the risk. This is important because, as this paper will show, quantifying this risk is not an easy task. Perhaps it will prove insurmountable, but there has not yet been enough effort to reach this conclusion.

There are other important policy questions that also demand a quantitative analysis of nuclear war risk. One concerns nuclear weapons launch alert status. The case for having nuclear weapons on high alert is based on the notion that doing so strengthens deterrence, because high-alert weapons can be launched more quickly, making it harder for the other side's first-strike attack to succeed. The case for having nuclear weapons on low alert is based on the possibility that high-alert weapons could more readily be launched accidentally or by rogue or unauthorized actors. Thus, launch alert policy faces a tradeoff between the risk of deterrence failure and the risk of accidental/unauthorized launch. Quantitative risk analysis is needed to evaluate this tradeoff.

There are also some more general policy questions that apply to a wide range of risks, including nuclear war. First, how much of a priority should nuclear war be? There are many issues that compete for attention, funding, and other scarce resources. Arguably, the larger the risk of nuclear war is, the more of a claim it has for these resources. Second, what are the best or most effective ways to reduce nuclear war risk? There are many actions that could potentially reduce the risk, from improving relations between nuclear-armed countries to developing resources to aid post-war survivors (Baum 2015a). Arguably, efforts to reduce nuclear war risk should focus on those actions that would cause the largest decrease in the risk.

It follows that a quantitative understanding of nuclear war risk is, or at least arguably should be, important for nuclear weapons policy. Therefore, the remainder of this paper focuses on the current state of quantitative analysis of nuclear war risk, the prospect for future progress, and what it all means for public policy and risk analysis research. Section 2 reviews prior literature. Section 3 presents an overview of the most detailed model currently available, that of Baum et al. (2018a) and Baum and Barrett (2018). Section 4 outlines an agenda for future research on nuclear war risk. Section 5 discusses the research and policy implications and concludes.

It should be noted that many of the issues raised here are not unique to nuclear war. To the contrary, many risks are difficult to analyze and/or have received little risk analysis attention by analysts or policy communities. This holds in particular for other global catastrophic risks. All global catastrophic risks face the same basic data challenge: no global catastrophe has ever destroyed modern global civilization. Many of the risks also face similar complexities. For example, Baum (2018) shows that asteroid risk—one of the few global catastrophic risks that has been analyzed at length—has highly uncertain human consequences. A major point of uncertainty concerns how well survivors would fare in a post-catastrophe world. The same uncertainty surrounds all global catastrophes that leave some survivors.

2. Prior Literature

This section reviews literature that analyzes the probability and severity of nuclear war, with emphasis on attempts to quantify probability and severity. This section does not attempt to cover the literature that presents more qualitative discussion of nuclear weapons issues and frames the discussion in terms of risk, such as Lewis et al. (2014), Borrie et al. (2017), and Acton (2018). This literature is often insightful and of relevance for the study of nuclear war risk, but it is beyond the scope of this paper.

2.1 The Probability of Nuclear War

The earliest dedicated analyses of the probability of nuclear war available in the public record appear to be by Bernard Bereanu of the Centre of Mathematical Statistics in Bucharest (Bereanu 1981; 1982; 1983), and by Michael Intriligator and Dagobert Brito, economists at University of California, Los Angeles and Tulane University (Intriligator and Brito 1981). Prior to these publications, i.e. over the first several decades after the invention of nuclear weapons, the literature contains relatively limited discussion of the probability of nuclear war.

The Bereanu papers model the probability of nuclear war due to false alarms from early warning system technical glitches. The false alarms are assumed to occur at random intervals following a Poisson process. The model compares the time it takes to assess whether the alarm is true or false to the time until adversary missiles reach their targets. If the alarm cannot be resolved before targets would be hit, it is assumed that the side experiencing the alarm will launch its nuclear weapons. The papers further assume that the time for missiles to reach their targets will steadily decrease, due to progress in missile technology. Under these assumptions, nuclear war will eventually occur "with probability 1" (Bereanu 1983, p.49, paper abstract). The papers propose negotiations on delivery systems to increase the time available to resolve alarms, and they propose nuclear disarmament as the policy needed to avoid nuclear war.

The various assumptions of the Bereanu model are made with little or no empirical justification and can readily be questioned. First, it is plausible that the rate of false alarms would tend to decrease over time due to improvements in warning system technology. Second, it is not a certainty that weapons would be launched if the false alarm is not resolved within the time for adversary weapons to reach their targets. Indeed, there are documented instances of military personnel and political leadership opting to not launch due to their own yet-unconfirmed suspicion of the alarm being false, such as the 1983 Stanslav Petrov incident and the 1995 Norwegian rocket incident.[4] There are even some nuclear-armed states, such as China, that are believed to typically keep their nuclear weapons in a low alert state, such that the weapons cannot be fired under such short notice. Third, the time for adversary weapons to reach their targets would not

[4] These and other false alarm incidents are described in Baum et al. (2018a).

necessarily continue to decrease. Indeed, missile speed has not changed substantially over the years.

Intriligator and Brito (1981) model the effect of nuclear proliferation on the probability of nuclear war. The model is a theoretical framework for evaluating the effect on the probability of war of additional states acquiring nuclear weapons. The paper does not attempt to quantify the effect, but instead presents qualitative discussion of likely trends. It considers the possibility of new nuclear-armed states initiating nuclear war as well as the possibility of them restraining nuclear war via deterrence and via potentially dominating the postwar order in the event that they are not party to the war. The discussion is largely theoretical and does not bring in significant empirical evidence to inform the analysis. A later publication (Brito and Intriligator 1996) proceeds along similar lines.

Marsh (1985) models the probability of the US launching nuclear weapons due to a false alarm of incoming attack. The study includes rich empirical detail on such matters as flight times of Soviet nuclear weapon delivery vehicles, US warning systems and decision structures, and the survivability of US nuclear forces. The study introduces a dataset of US false alarms during 1977-1983 that was subsequently used by Wallace et al. (1986) and Barrett et al. (2013). The data suggest one false alarm per year. For certain launch postures (in particular "launch under attack"), alarms from both radar and satellite are needed ("dual phenomenology"). Both alarms would need to occur during a narrow window corresponding to the flight time of the Soviet missile, which the study calculates to be 27 minutes for ICBMs and 9 minutes for SLBMs. That corresponds to a 0.000051 annual probability of two concurrent false alarms for ICBMs and a 0.000017 annual probability for SLBMs, or approximately once per 20,000 years for ICBMs or 60,000 years for SLBMs (p.68).

Paté-Cornell and Neu (1985) model the effect of US command, control, communications, and intelligence (C3I) systems on the probability of nuclear war between the US and the Soviet Union. C3I systems are supposed to provide national leadership with accurate information on whether the nation is under attack, and to faithfully relay any launch orders that the leadership decides to make. The study models an array of scenarios based on whether the Soviet Union has launched an attack, whether US C3I correctly assesses the presence or absence of an attack, whether or not the US national leadership decides to launch an attack based on the information that US C3I has provided it, and whether or not US C3I accurately relays launch orders to weapon operators. The model additionally explores different C3I configurations that can affect these various probabilities, such as launch on warning vs. launch on impact. Model parameters are quantified using illustrative point estimates based on the author's judgments that are "deliberately arbitrary" and "bear no known relation to any realistic probabilities" (p.132). The study finds that the probability of inadvertent US nuclear launch due to C3I false alarm "dominates" the probability of US non-launch due to C3I failing to report an incoming attack (p.135), though given the allegedly arbitrary nature of the parameter estimates, this finding may have no real-world meaning.

Wallace et al. (1986) model the probability of the US launching nuclear weapons due to a false alarm of incoming attack. This study combines the 1977-1983 US false alarm data from Marsh (1985) with information on the time available to resolve false alarms. The underlying idea is that if an alarm cannot be resolved, then it may be interpreted as a real attack, thereby prompting launch in what is presumed to be a counterattack. The study calculates probabilities of false alarms occurring during major crises (such as the Cuban missile crisis), given the frequency of false alarms and the duration of a given crisis. However, the study falls short of calculating the probability of nuclear war because it does not consider the frequency of crises. Additionally, it does not rigorously quantify the probability of a false alarm prompting a nuclear weapon launch: it focuses on the time available to resolve alarms and not the human decision process of ordering launches.

Avenhaus et al. (1989) model the total probability of nuclear war. The paper explores how changes in the annual probability of nuclear war affect the long-term probability. The analysis is entirely theoretical and does not appear to have any basis in actual estimates of the probability of nuclear war. Instead, it is essentially just an inquiry into the mathematics of sequences of probabilities that happens to be framed in the context of nuclear war but could just as easily be for any ongoing probability.

Paté-Cornell and Fischbeck (1995) apply Bayesian probability theory to the interpretation of C3I signals by the US President. The study is not an analysis of the probability of nuclear war per se, but instead is an analysis of the probability of incoming attack that the President is likely to assign in the event that US C3I indicates an incoming attack. The study assumes that the President's reasoning conforms to Bayesian probability theory. The study further assumes certain specifics about the President's beliefs, for example that the President's prior probability of attack follows a beta distribution. The study postulates that, with the Cold War having ended, the probability of incoming attack may be low relative to the probability of C3I false alarm, and that the President may overestimate the probability of incoming attack in the event of a C3I alarm unless the President's thinking conforms with Bayesian probability theory.

Hellman (2008) models the probability of Russia-U.S. nuclear war that is caused by a crisis similar to the Cuban missile crisis. The model includes the frequency of events that could escalate into such crises and the conditional probabilities of escalation from initial event to crisis, from crisis to nuclear weapons launch, and from nuclear weapons launch to all-out nuclear war. The study uses historical data for initial event frequency and escalation to crisis. There is no historical data for escalation to nuclear weapons launch and all-out nuclear war, so the study uses ranges of probabilities. The study calculates the probability of this type of nuclear war as being in the range of $2x10^{-4}$ to $5x10^{-3}$ per year. Arguably, ranges of probabilities should have also been used for the first two parameters, which are also uncertain. Furthermore, this study uses a sparse information set to quantify its parameters, suggesting a significant amount of ongoing uncertainty.

Lundgren (2013) models the probability that nuclear war could have occurred during the Cold War. The model includes crises, false alarms, and conventional war escalating to nuclear war. The model uses a 21.3% probability for nuclear war via the Cuban missile crisis based on personal estimates of President Kennedy and his national security advisor, McGeorge Bundy. Many of the other probability estimates are the author's personal estimates and are not easily assessed. The study also does not consider uncertainty in any of its parameter estimates. The study calculates a 61% chance that nuclear war could have occurred during the Cold War. Of course, it is now known with certainty that nuclear war did not occur during the Cold War, and present and future circumstances are different from the Cold War.

Barrett et al. (2013) model the probability of inadvertent Russia-U.S. nuclear war. As defined in this paper, inadvertent nuclear war occurs when one country misinterprets a false alarm as a nuclear attack by another country and launches nuclear weapons in what it mistakenly believes is a retaliation but is in fact the first strike. The study models the process of a false alarm making its way through the launch decision process. The study uses the Marsh (1985) false alarm data, assuming that the ongoing false alarm rate is consistent with this older dataset. The study also uses probability distributions for uncertain parameters. The study calculates probability distributions for the rate of inadvertent Russia-U.S. nuclear war under two sets of assumptions. The distributions are quite wide, with the 5% to 95% ranges spanning from 0.0002 to 0.07 and from 0.00001 to 0.05 depending on the assumptions.

2.2 The Severity of Nuclear War

The literature on the severity of nuclear war is more diffuse and more difficult to summarize. Thus, this section will only cover a few select highlights from this literature.

Perhaps the first analysis of the severity of nuclear war is Konopinski et al. (1946), a study completed as part of the Manhattan Project. This study examined the possibility of nuclear detonations igniting the atmosphere, resulting in global catastrophe. The study concluded that ignition was unlikely but did not definitively rule it out. The study was conducted prior to the Trinity test, which was the first-ever nuclear detonation. Had the study found ignition to be more likely, the Trinity test may not have proceeded.

An especially detailed study of the severity of nuclear war is Glasstone and Dolan (1977), published jointly by the US Departments of Defense and Energy. This study documents several physical effects of nuclear war: air blast, ground shock, thermal radiation, ionizing radiation, and electromagnetic pulse. The study presents the physics of these effects in considerable detail. It also covers secondary effects on built infrastructure and human bodies (i.e., medical effects). Other secondary effects, such as economic and political effects, are not covered. The study contains some quantitative analysis but does not seek to tabulate the net severity of nuclear detonations, nor does it consider the aggregate severity of nuclear war.

OTA (1979), a study by the US Office of Technology Assessment and commissioned by the US Senate Committee on Foreign Relations, assesses a range of consequences of nuclear war. It emphasizes that "the effects of a nuclear war that cannot be calculated are at least as important as those for which calculations are attempted" (p.3). This line specifically refers to the calculations of military planners, which focus on more predictable consequences of nuclear war and exclude less predictable consequences such as social and economic disruption. The study analyzes four nuclear war scenarios: attacks on individual cities (using Detroit and Leningrad as examples), 10-missile attacks on oil refineries, counterforce attacks on ICBM silos, and all-out counterforce and countervalue attacks. It also considers the relative advantages and disadvantages of the US and Soviet political-economic systems for managing the aftermath of nuclear war.

Turco et al. (1983) presents the first scientific study of the global environmental consequences of nuclear war known as nuclear winter. This study focuses exclusively on environmental effects and does not seek to characterize impacts in human terms. Several studies have since examined the environmental consequences. For example, Robock et al. (2007) use more advanced climate models, finding less intense but more durable effects than Turco et al. (1983), while Reisner et al. (2018) use more advanced fire models, finding less smoke entering the stratosphere relative to previous studies.

Ehrlich et al. (1983) studies ecological consequences of nuclear war from ionizing radiation and various effects related to nuclear winter. The study anticipates massive ecological harms, including "the extinction of a major fraction of the plant and animal species on Earth", and finds that human extinction "seems unlikely" but "cannot be ruled out" (p.1299). Loss of civilization in the Northern Hemisphere and possibly its entire population are seen as more likely possibilities. However, these possible human effects are not based on any careful analysis. Instead, the analysis focuses on general ecological effects, primarily to nonhuman species.

Cantor et al. (1989) is a rare extended inquiry into the economic consequences of nuclear war, produced by Oak Ridge National Laboratory on behalf of the U.S. Federal Emergency Management Agency. The study is framed generically in terms of social cataclysms and uses nuclear war as a central example. The study explores the possible forms of economic exchange in the aftermath of nuclear war. It considers possibilities such as the loss of property rights, the use of barter instead of money, the loss of trust in fiduciary authorities, and disruptions to transportation and labor. The study draws on literatures from anthropology, economics, and sociology, and it reflects on the challenge of scientifically analyzing such an unprecedented event. It does not attempt to quantify the economic consequences of nuclear war, but nonetheless highlights why economic consequences can be an important factor to the overall severity of nuclear war.

Toon et al. (2007) assess a range of human and environmental consequences of nuclear war and nuclear terrorism. The study models human casualty and fatality rates as a function of distance from ground zero based on Hiroshima and Nagasaki data. Using this model, it presents calculations of casualties and fatalities from a similar (15KT) detonation in several nuclear terrorism and nuclear war scenarios. Calculations are presented as point estimates and do not account for uncertainty in the underlying model or the use of nuclear weapons with other yields. Human harms from ionizing radiation, including medical effects and territory abandonment, are described but not quantified. (There is quantification of some physical processes involving ionizing radiation.) Analysis of global environmental effects focuses on the amounts of soot produced and the corresponding effects on atmospheric chemistry; human harms are not considered.

EMP Commission (2008) presents a detailed analysis of the effects of electromagnetic pulse. The Commission was created by the 2001 US National Defense Authorization Act. The EMP Commission (2008) study presents an especially detailed analysis of the effects of nuclear war on civil infrastructure. The study focuses on the considerable effects of electromagnetic pulse on infrastructure, but much of it also applies to effects from other aspects of nuclear war. For example, disruptions to energy systems, telecommunications, food and water provision, and government functioning, all covered in EMP Commission (2008), can also occur from the direct damages from low-altitude nuclear detonations (blast, fire, etc.). The study describes the effects in detail but does not present aggregate quantifications of severity.

Robock (2010) surveys the scientific literature on nuclear winter and discusses some potential human harms. The study finds that "most of the world's people are threatened with starvation following a full-scale [Russia-US] nuclear war" (p.424). The study further states that "Although extinction of our species was not ruled out initial studies by biologists [such as Ehrlich et al. (1983)], it now seems that this would not take place. Especially in Australia and New Zealand, humans would have a better chance to survive." It should be noted that the phrasing "a better chance to survive" continues to not rule out human extinction. Furthermore, the study focuses on environmental effects, not human consequences, and thus is arguably not well-positioned to evaluate prospects for human survival.

Helfand (2013) quantifies the human harms from nuclear winter in an India-Pakistan nuclear war scenario. The study finds that two billion people could be at risk of starvation. The study only claims that this number of people would be at risk of starvation, not that they in fact suffer or die from starvation. The analysis is based on crop modeling under nuclear winter climatic conditions and data on global food insecurity. The underlying idea is that nuclear winter would reduce food availability, which is especially worrisome for the present-day population that already faces food scarcity. While this underlying idea is likely to be robust, the two billion estimate is more suspect. Throughout the study, point estimates are used for highly uncertain parameters, and the uncertainty is seldom acknowledged. For example, the study states that "Even if agricultural markets continued to function normally, 215 million people *would* be added to the rolls of the malnourished over the course of a decade" (p.2, emphasis added), suggesting that it is known that this exact number of people would become malnourished under the described scenario. The study also identifies, but does not attempt to quantify, two additional effects that could factor significantly in the total severity: the possibility of food scarcity to cause or worsen disease outbreaks and violent conflicts. These possibilities speak to the considerable uncertainty pervading attempts to quantify the severity of nuclear winter and other impacts of nuclear war.

Fihn (2013) exemplifies the studies of the consequences of nuclear war undertaken by the portion of the international community that seeks more rapid nuclear disarmament. This publication presents discussions of a range of consequences: medical, environmental, agricultural, economic, and political. It also includes case studies of several actual and potential nuclear detonations. It includes technical and quantitative analyses as well as attention to the human side, for example noting "The vast majority of injured people would die alone without so much as a human hand or voice to comfort them and without any relief for their agonising pain" (p.23). The publication concludes that the international community should "declare both the use and the possession of nuclear weapons as unacceptable, as there is no legitimate situation in which the impact of the use of a nuclear weapon can be justified" (p.100), though it considers neither the probability of nuclear weapon use nor the risk of violence in a world without nuclear weapons.

Frankel et al. (2013) evaluate the state of knowledge about the physical consequences of nuclear detonations. This study reviews data from test detonations and extrapolations based on underlying physical mechanisms. It covers a range of effects, with emphasis on surprises such as electromagnetic pulse, ozone depletion, and nuclear winter. A central theme is that the physical consequences remain uncertain, especially for large-scale nuclear war. Echoing OTA (1979), this study expresses concern about a tendency to "underestimate consequences by concentrating on selected physical phenomena that cause calculable damage to targets of interest to military planners" (p.31).

2.3 Overarching Themes in the Prior Literature

In consideration of the prior literature for both the probability and severity of nuclear war, several themes emerge. First, the literature has many gaps. Probability studies tend to focus on specific nuclear war scenarios, while the one study attempting to cover the total probability (Avenhaus et al. 1989) has significant methodological limitations. Impacts studies tend to focus on the more readily quantifiable harms, especially physical and environmental effects and medical harms from direct exposure to nuclear detonations, while studies that cover other harms tend not to quantify the aggregate severity from these harms (e.g., Cantor et al. 1989; EMP Commission 2008).

Second, the risk of nuclear war is not easy to quantify. Attempts to quantify the probability are generally incomplete and easy to poke holes in. Studies of the impacts often do not even attempt quantification, and when they do, it is only for a few relatively simple portions of the impacts. For both probability and impacts, quantification is challenged by pervasive complexities and a lack of empirical data.

Third, it can be argued that the literature is not particularly extensive. Section 2.1 has a more-or-less comprehensive survey of the probability literature; this is really not much for a topic that has been studied for almost 40 years. Section 2.2 does not have a comprehensive survey of the impacts literature, but the vast majority of this literature, including most of the studies in Section 2.2, is oriented toward general descriptions of impacts and not toward risk analysis. Analysts seeking to answer basic questions—such as what the total risk of nuclear war is and how the risk could be affected by various policies—have little in the way of resources to draw on. While the risk is difficult to quantify, quite a lot more could be done to that end.

3. The GCRI Model

In recognition of the shortcomings of the prior literature, the GCRI model covers the entire risk. The model is summarized in Figure 2.

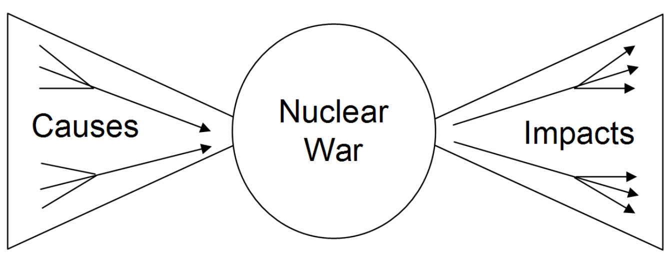

Figure 2. Summary of the GCRI model for the risk of nuclear war.

Figure 2 resembles a "bowtie" model commonly used in risk analysis.[5] The element on the left depicts the set of causes that can form nuclear war scenarios; this is used to model the probability of nuclear war. The element in the center depicts the details of the nuclear war itself, such as which countries participate, how many nuclear weapons are detonated, and which targets are struck by the nuclear detonations. The element on the right depicts the impacts of nuclear war, with each detonation branching out into a range of impacts. Work to date has focused on developing the model structure for probability and impacts. The model structure for the details of the nuclear war itself remains to be

[5] Bowtie models typically put threats in the left bow, consequences in the right bow, and the hazard in the middle. For discussion, see e.g. https://www.cgerisk.com/knowledgebase/The_bowtie_method.

completed, as does quantifying parameters in each of these models. What follows is a summary of the probability and impacts models. Full detail can be found in Baum et al. (2018a) and Baum and Barrett (2018).

3.1 The Probability Model

The probability model has two main branches, covering two major types of nuclear war scenarios: intentional first strike and first strike intended to be retaliation. Intentional first strike occurs when a country correctly believes that it is not under nuclear attack and makes the decision to initiate nuclear war. First strike intended to be retaliation occurs when a country incorrectly believes that it is under nuclear attack when in fact it is not under nuclear attack, and then makes the decision to launch nuclear weapons in what it believes is retaliation but is in fact the first strike. The two model branches are shown in Figure 3.

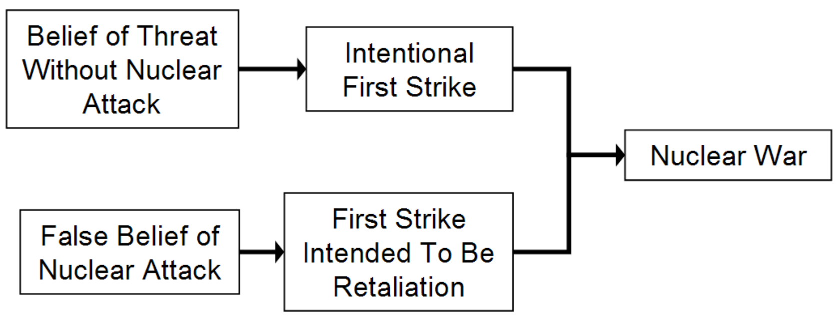

Figure 3. Two main branches of the GCRI nuclear war probability model.

The distinction between the two main branches is central to at least one important policy decision, concerning nuclear weapon launch alert status. When weapons are at high alert, they can be launched more rapidly in response to warnings of incoming attacks. This is believed to strengthen nuclear deterrence by making it harder for one side to destroy the other side's nuclear weapons in a surprise first-strike attack. However, high alert is also believed to increase the potential for accidental or unauthorized launch of nuclear weapons because weapons on high alert are easier to launch. This is essentially a tradeoff between the probability of intentional first strike and the probability of first strike intended to be retaliation: higher alert status could decrease the probability of intentional first strike (by strengthening deterrence) and increase the probability of first strike intended to be retaliation (by making it easier to launch nuclear weapons based on faulty information).

The model in Figure 3 can be translated into a probability equation in order to assess the probability of nuclear war and inform decisions such as launch alert status. The equation can be written is as follows:

$$\lambda_{NW} = \lambda_T * P_T + \lambda_F * P_F \quad (1)$$

In Equation 1, λ_{NW} is the annualized rate of nuclear war; λ_T is the annualized rate of events that could provoke intentional first strike; P_T is the conditional probability that one such event prompts an intentional first strike; λ_F is the annualized rate of a false belief of being under nuclear attack; and P_F is the conditional probability that the false threat prompts a first strike that is intended as retaliation. Annualized rates correspond to the probability of nuclear war occurring in a one-year interval; for more on the relation between rates and probabilities, see Baum et al. (2018a).

In terms of Equation 4, the launch alert policy decision can be conceptualized as an optimization problem in which the launch alert level is selected to minimize λ_{NW}. Higher launch alert levels may decrease P_T by persuading countries that their intentional first strikes will be met with devastating retaliation. Higher launch alert levels may also decrease λ_T by motivating countries to avoid the sorts of conflicts and crises that could provoke intentional first strike. On the other hand, higher launch alert levels may increase P_F by making it easier for first strike attacks to be initiated. Higher launch alert levels may also increase λ_F by lowering the threshold for a country to believe it is under nuclear attack. Insofar as launch alert level does indeed pose a tradeoff between (λ_T * P_T) and (λ_F * P_F), it should be of considerable policy interest to assess which launch alert level minimizes λ_{NW}. This is one potential application of the probability model.

The rest of the probability model consists of details for each of the two main model branches. Figure 4 presents detail of the top branch. It includes two main pathways to intentional nuclear war: intentional escalation and inadvertent escalation. Intentional escalation occurs when one country's leadership makes the decision to act in a way that prompts another country's leadership to respond with a nuclear attack. Inadvertent escalation occurs when one the escalatory actions occur without any decisions from national leadership, such as in the "fog of war" (Posen 1991). Finally, both intentional and inadvertent escalation can occur during a conventional direct war (such as World War II), a conventional proxy war (such as the Vietnam War), or a non-war crisis (such as the Cuban missile crisis).

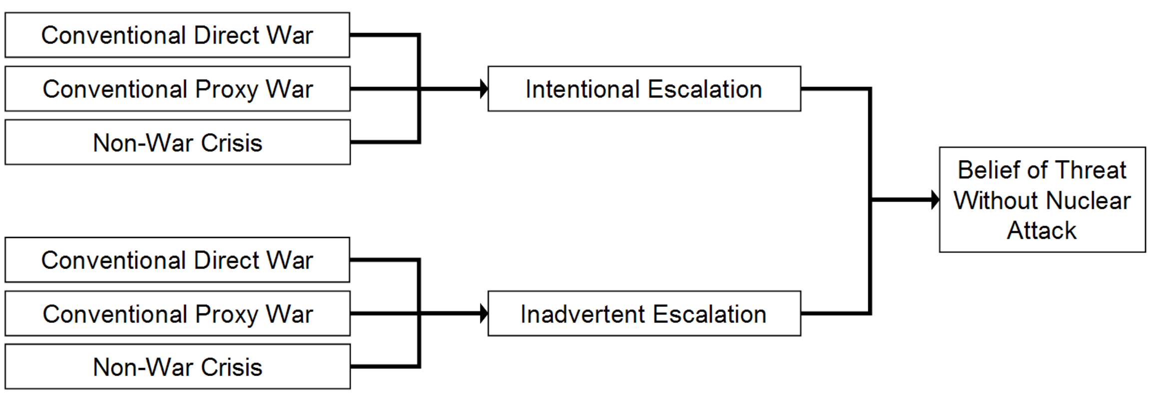

Figure 4. Top branch of the GCRI nuclear war probability model.

Figure 5 presents detail of the bottom branch. It includes two main pathways to nuclear war from a first strike intended as retaliation, based on two types of events that could cause a country to mistakenly believe it is under nuclear attack: non-war nuclear detonations and false alarms. Non-war nuclear detonations are any detonation that is not intended as an attack by the authorized leadership of another country. Non-war nuclear detonations include unauthorized detonations (such as by rogue actors within a nuclear-armed country or by terrorists who commandeer a country's nuclear weapons), detonations of nonstate nuclear weapons (if terrorists or other nonstate actors can build their own nuclear weapons), and accidental detonation of either domestic (a country's own) nuclear weapons or foreign (another country's) nuclear weapons. False alarms include events that look like nuclear attacks, including military exercises and nonmilitary events (such as scientific rocket launches), and monitoring system mistakes, including mistakes due to human error and glitches in monitoring system technology.

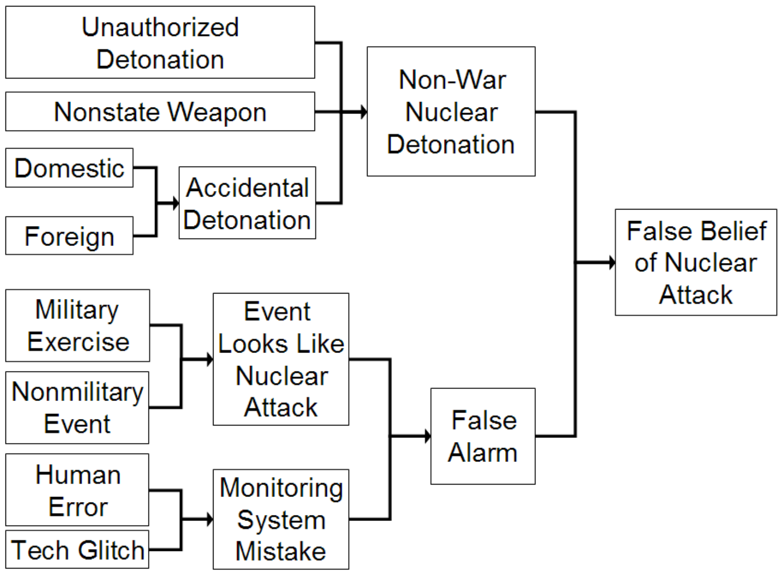

Figure 5. Bottom branch of the GCRI nuclear war probability model.

The probability model details can offer a wealth of valuable information, especially if model parameters can be quantified. For example, the probability of inadvertent escalation could inform decisions about how aggressive to be in conventional wars and crises. Some nuclear threats are often treated as "the threat that leaves something to chance" (Schelling 1960); which threats are made (and how) could be informed by (among other factors) exactly what that chance is. As another example, the various probabilities of different types of false alarms could inform decisions for how to allocate resources to reduce the probability of false alarm.

As a starting point for quantifying probability model parameters, Baum et al. (2018a) compile a dataset of 60 historical incidents that may have threatened to become a nuclear war. The dataset includes the one actual nuclear war (World War II) and 59 events that went partway towards nuclear war (such as the Cuban missile crisis). Further work is needed to assess how close each incident came to nuclear war and the ongoing probabilities of similar incidents, both of which are important steps toward quantifying the probability of various types of nuclear war.

Quantifying how close each incident came to nuclear war would be a subtly challenging endeavor. The incidents are all prone to historical interpretation. Indeed, analysts disagree on how close they were to nuclear war—for example, Lewis et al. (2014) consider them to have come pretty close, while Tertrais (2017) disagrees. One valuable contribution would be to analyze this debate in consideration of the broader study of the interpretation of near-miss events in risk analysis (e.g., Dillon et al. 2014).

3.2 The Impacts Model

The probability model has five main branches, covering five major types of impacts of nuclear detonations: thermal radiation, blast, ionizing radiation, electromagnetic pulse, and human perceptions. The first four branches are widely documented, such as in the literature surveyed in Section 2.2. The human perceptions branch covers the social, political, and cultural reactions that humans can have to nuclear detonations. For example, the detonations in Hiroshima and Nagasaki may have shifted attitudes toward warfare and military conduct in ways that heavily structured the Cold War and other adversarial relationships. The five model branches are shown in Figure 6.

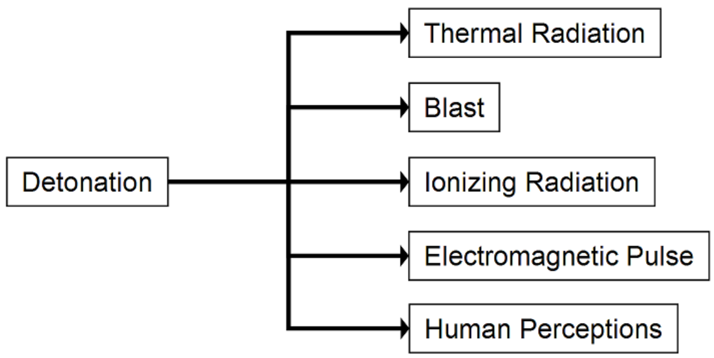

Figure 6. Five main branches of the GCRI nuclear war impacts model.

The rest of the impacts model is substantially more complex than the probability model, and likewise cannot be shown in full in this paper. (It is contained in full in Baum and Barrett 2018). Instead, this section will present select portions of the model in order to provide a general impression of it and to discuss some implications for research and policy.

A central feature of the impacts model is the use of modules that repeat in multiple model branches and interconnect with each other. The modules are essentially equivalent to modules or objects in object-oriented computer programming. Quantitative forms of the impacts model could likewise be implemented with such programming. As with other applications of object-oriented programming, the model's use of modules is done because some types of impacts recur in different parts of the model. The model contains 15 modules: fire, blocked sunlight, damage to infrastructure, water supply disruption, agriculture disruption, food insecurity, healthcare disruption, infectious disease, transportation disruption, transportation systems disruption, energy supply disruption, satellite disruption, telecommunications disruption, shifted norms, and general malfunction of society.

To illustrate the modular nature of the module, the section will now present some model detail related to nuclear winter, which is an especially important potential impact of nuclear war. Nuclear winter comes largely from thermal radiation causing fire, which blocks sunlight. Figure 7 shows the model's module for blocked sunlight. There are two main sets of impacts: agriculture disruption and changes to solar, wind, and hydro energy. As shown in Figure 8, agriculture disruption can cause changes to food consumption and a reduction in greenhouse gas emissions, the latter due to the large amount of greenhouse gas emissions currently produced by agriculture. As shown in Figure 9, the shifts in energy from blocked sunlight can disrupt energy supplies and can increase greenhouse gas emissions, as declines in renewable energy prompt increases in fossil fuel energy. Finally, Figure 10 shows the food insecurity module, whose impacts include the general malfunction of society due to the loss of labor and the outbreak of infectious diseases.

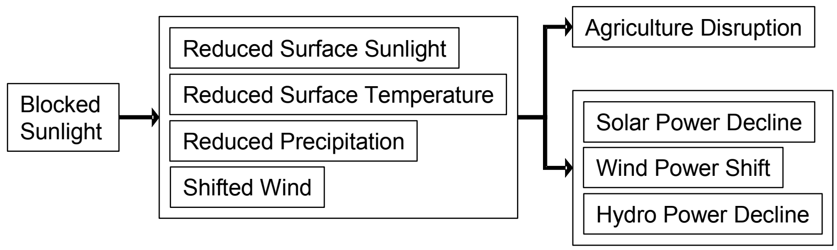

Figure 7. The blocked sunlight module.

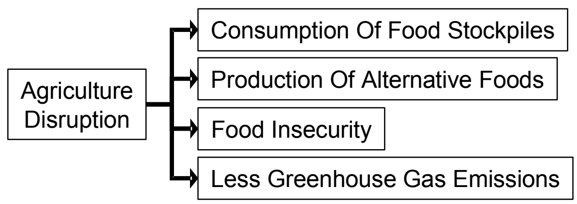

Figure 8. The agriculture disruption module.

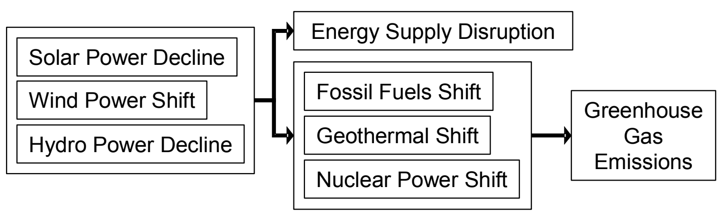

Figure 9. Model detail for shifts in energy from blocked sunlight.

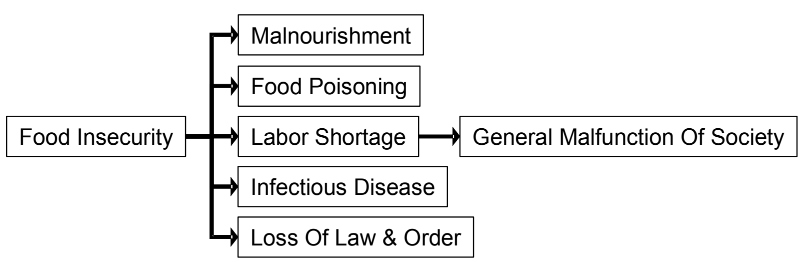

Figure 10. The food insecurity module.

Figures 7-10 show that the impacts of nuclear war could in turn affect at least two other global catastrophic risks: climate change and infectious diseases. The connection to infectious diseases has briefly been identified in previous literature (e.g., Helfand 2013) but has not been explored in significant detail, even though this is potentially one of the largest impacts of nuclear war. For comparison, the 1918 "Spanish" flu outbreak was arguably the largest impact of World War I. (The outbreak killed many more people than the war itself and may have been substantially milder if the war had not occurred.) The connection to climate change has not been discussed to any significant extent in prior literature and could also be an important factor.

The importance of including these indirect impacts of nuclear war is consistent with a theme in some of the literature surveyed in Section 2.2, especially OTA (1979), Cantor et al. (1989), and Frankel et al. (2013). Instead of starting by modeling the portions of the impacts that are easiest to model, this model starts by identifying the full range of potential impacts. Climate change and infectious disease are examples of impacts that are not included in most studies of nuclear war impacts and are not easy to model but could be major factors in the total severity. Future research is needed to quantify the severity of each of the various impacts.

4. Nuclear War Decision-Making

While the analysis of nuclear war risk slowly chugs along, a variety of important decisions related to nuclear war are continually being made. Many of these are informed at least in part by aspects of nuclear war risk, such as disarmament advocates' concern for the impacts of nuclear war and deterrence advocates' concern for the probability of nuclear vs. non-nuclear war. However, this use of risk thinking has been somewhat superficial and largely disconnected from the various attempts to more carefully analyze the risk.

The disconnect is especially vivid in a passage from Paté-Cornell and Fischbeck (1995, p.31), which describes a hypothetical decision in which two Presidential advisors provide the President with advice based on two distinct nuclear war scenarios:

> …they propose two different probabilities (0.2 and 0.3) that an attack is underway. Assume also that initially, having heard both arguments, the President gives each hypothesis a probability of 0.5 and that he has adopted as a measure of his own degree of belief the two estimates of the probability of attack conditional on the two hypotheses (0.2 and 0.3)… The mean prior probability that an attack is under way is therefore 0.25.

The analysis in this passage is logically coherent, but it has no apparent connection to actual US Presidential decision-making. While it is not the place of the current paper to speculate on the nature of US Presidential decision-making, it may nonetheless be plausible that, for at least some US Presidents, the passage does not describe how they think. Indeed, the US voters (or, more precisely, the US electoral college) have yet to elect a President with the sort of formal risk analysis background one may need to think in the terms described in the passage.

This passage is indicative of what I believe to be a wider tendency of risk analysts assuming, or at least hoping, that decision-makers share their analytical and ethical perspective, such that the risk analysts' analysis could strongly inform important policy decisions. This phenomenon is hardly unique to nuclear war, but nuclear war offers an especially compelling case, given that many of the essential decisions must be made by the US President, the heads of other nuclear-armed states, and other top government officials. To be sure, there are a wide range of decisions to be made by a wide range of people that can affect the risk of nuclear war, including decisions by ordinary citizens, technical experts, and other people from outside the top echelons of government (Baum

2015a). But these other populations are typically not seeking input from risk analysis either.

This circumstance may merit a more pragmatic approach by risk analysts. As elaborated in Baum (2015d) and Baum and Barrett (2017), one approach involves analysts and other like-minded colleagues reaching out to decision-makers in order to learn the decision-makers' perspectives and opportunities and formulate policy ideas that make sense to them. Such an approach can be successful, but it places a considerable burden on analysts and their colleagues. Furthermore, any success could be transient, requiring analysts and colleagues to do customized outreach and policy formulation for each decision, with decision-makers otherwise poised to proceed in their own particular ways.

An alternative approach may be to advocate for a risk perspective among decision-makers. The aim would be to create durable interest in treating risk as an important factor in decision-making and likewise in the use of careful risk analysis. The case for risk in nuclear war decision-making arguably should be compelling, for reasons described throughout this paper, in particular for the central role that risk can play in policy decisions like nuclear disarmament and launch alert status. In my own brief experience engaging with nuclear weapons policy communities, I have seen enough interest in the risk perspective to believe there should be more effort to promote the risk perspective within these communities.

One important and very immediate decision is on whether analysts and their colleagues focus their effort on additional analysis or on outreach to policy communities. At this time, I believe the main limiting factor is interest from policy communities, and that the focus should therefore be on outreach. There has been significant progress in the research literature, including both the literature surveyed in Section 2 and the GCRI model outlined in Section 3. Yes, this research has major limitations, such that it cannot yet provide detailed guidance to policy decisions. Likewise, additional research progress can make risk more useful and compelling to decision-makers. But the policy debate is not up to speed on even the limited existing literature, or on a more basic risk perspective. Until policy communities have a greater interest in nuclear war risk analysis, and greater sophistication in their use of it, there is little reason to continue producing nuclear war risk analyses. Furthermore, if they do become more interested in nuclear war risk analysis, then they may also create more institutional support for the analysis, which could accelerate research progress. One reason for further nuclear war risk analysis is to develop risk-reduction solutions that appeal to policy communities regardless of their interest in risk, as described above and in Baum (2015d) and Baum and Barrett (2017), but even this approach may be limited mainly by interest from policy communities. Thus, the case for more outreach would appear to be robust.

5. Conclusion

Nuclear war is an important risk. Analysis of the risk, including quantifying its probability and severity, could and arguably should yield valuable information for many important decisions that can affect the risk. Nuclear disarmament and nuclear weapon launch alerts status are two examples of decisions that pose tradeoffs between different risks and therefore benefit from the capacity to quantitatively evaluate the tradeoffs.

However, seven decades of scholarship on nuclear war risk, from the Manhattan Project study of Konopinski et al. (1946) to the GCRI model of Baum et al. (2018a) and Baum and Barrett (2018), has largely failed to inform these decisions. There are several reasons for this. Nuclear war is a difficult risk to quantify. The body of research remains fairly small. And decision-makers have generally not sought out risk analysis to inform their decisions.

There is no escaping the fact that nuclear war is a difficult risk to quantify, but progress can be made on both the research and the decision-making. At this time, it appears that the limiting factor is in the use of risk analysis in decision-making, such that analysts and their colleagues should focus on outreach to decision-makers instead of further research. However, further research can still be helpful, including to demonstrate the usefulness of risk analysis to decision-makers.

Nuclear war is not the only risk that faces these challenges. Indeed, all of the global catastrophic risks do to varying extents, as do many other risks. Nuclear war is thus both an important risk in its own right and also a valuable case for analyzing and managing risks, especially global catastrophic risks. Given the very high stakes, it is important that we continue to try to get the details right.

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