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A Model for the Impacts of Nuclear War

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Abstract

The total impact of nuclear war is a major factor in many important policy questions, but it has gotten little scholarly attention. This paper presents a model for calculating the total impacts of nuclear war. The model includes physical, infrastructural, and social impacts as they affect human lives. The model has five main branches corresponding to the five main types of effects of nuclear weapon detonations: thermal radiation, blast, ionizing radiation, electromagnetic pulse, and human perceptions. Model branches contain extensive detail on each of these effects, including interconnections between them and connections to other major risks including global warming and pandemics. The paper also includes background information on impacts analysis and modeling to help readers understand how to think about the impacts of nuclear war, including discussion of important attributes of nuclear war such as the number and yield of weapons detonated and the location of their detonation.

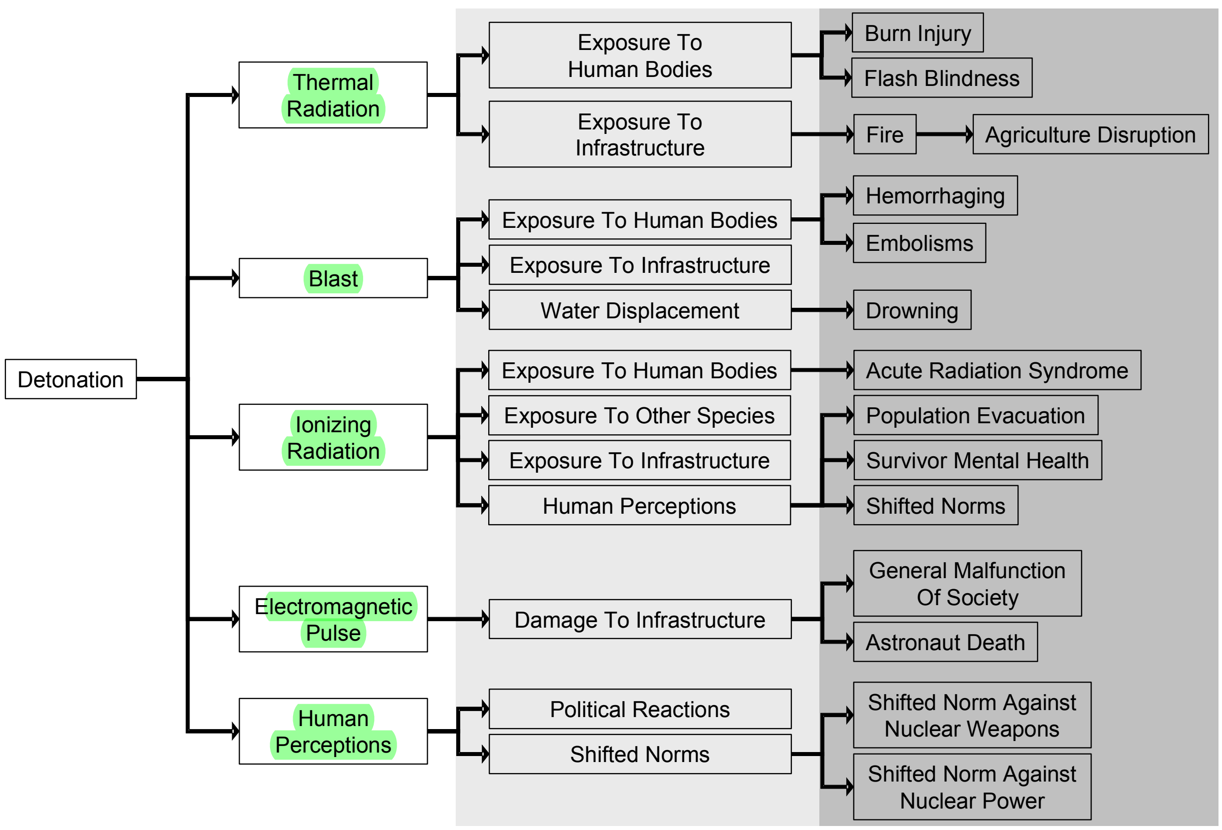

Figure 1. Summary of the nuclear war impacts model. The five model branches correspond to the five main impacts of nuclear weapon detonations. The light shaded area shows all of the second-level model elements. The dark shaded area shows select lower-level model elements. Interconnections between the model branches are not shown. The total impacts of nuclear war are a function of the impacts of each nuclear detonation that occurs during the war.

Introduction

Nuclear wars are rare. In the seventy years since nuclear weapons were invented, there has been only one: World War II. The ongoing probability of nuclear war is not precisely known, but as long as some states continue to possess nuclear weapons or the capacity to produce them, the probability is not zero. This raises the question: if another nuclear war occurs, what would the impacts be?

This paper presents a graphical, modular model for calculating the total impacts of nuclear war. The core feature of the model is its wide range of types of impacts. The model aims to include every major type of impact that nuclear war can have. To identify types of impacts, we reviewed the literature on both nuclear war and on a range of other catastrophe scenarios. The model can readily be extended to accommodate any additional types of impacts identified in the future.

The model can be used to produce estimates of the severity of the impacts of specific nuclear war scenarios. However, this paper stops short of producing such estimates. At this stage of the research, estimates of the severity of nuclear wars would require considerable guesswork and are likely to be inaccurate. Rigorous quantification of the severity using this paper's modeling framework and/or other models is an important task for future research.

Why This Is Important

The impacts of nuclear war is a key factor in a number of important policy questions. Here are some examples:

How much should nuclear war risk be prioritized relative to other issues, including nuclear terrorism risk and other global catastrophic risks? Policy makers have limited attention and a virtually unlimited range of issues they could focus on. The more severe the impacts of nuclear war are, the more it merits attention.

Which policies would do the most to reduce the risk of nuclear war? There are many policies that can reduce nuclear war risk. Policy makers should focus on the most effective policies, including policies for reducing the severity of the impacts of nuclear war.

Which efforts to reduce the probability of nuclear war should be prioritized? Some nuclear war scenarios could have significantly more severe impacts than others. All else equal, priority should go to reducing the probability of scenarios with more severe impacts.

How rapidly should states disarm nuclear weapons? The international community is in broad consensus in favor of nuclear disarmament. However, there is a major debate about how rapidly nuclear disarmament should proceed. The more severe the impacts of nuclear war are, the stronger the case may be for disarming rapidly.

What preparations should be made to aid nuclear war survivors? In the event of a nuclear war, survivors could face major of challenges. Preparations made prior to the war could help them. Modeling the severity of the impacts can show which preparations would be likely to make the most difference.

Prior Work

The impacts of nuclear war have been studied since before nuclear weapons even existed. Perhaps the first study of the impacts came as part of the Manhattan Project, the secret U.S.

group that first developed nuclear weapons during WWII. Some Manhattan Project physicists worried that even a single nuclear detonation would ignite the atmosphere and end all life on Earth. They considered this potential impact unlikely, but they nonetheless commented that "the complexity of the argument and the absence of satisfactory experimental foundations makes further work on the subject highly desirable" (Konopinski et al. 1946). It is now known that nuclear weapons do not have this effect, since there have been by now numerous nuclear detonations, none of which have ignited the atmosphere.

The atomic bombings of Hiroshima and Nagasaki provide the two core data points on which much of the study is based. They have been used to model the fatalities that could occur following nuclear detonations in other cities (Toon et al. 2007). The long time period that has elapsed since the bombings has permitted long-term longitudinal study of the medical effects of exposure to the ionizing radiation released in nuclear detonations (Ozasa et al. 2011; Doss et al. 2012). Historians have studied and debated the military and geopolitical impacts of the bombings, such as whether they caused Japan's surrender (Wilson 2013). There has even been some sociological study of the bombings' cultural impacts (Broderick 1996).

There have been no nuclear wars since WWII, but there have been approximately 2,000 test detonations. These detonations were carefully studied and yielded a lot of information, especially about the physical effects of nuclear detonations. The detonations were conducted mainly in locations isolated from human populations and thus provide less information about human impacts. Exceptions include the radiation exposure of residents of test areas, such as certain Pacific islands (Takahashi et al. 2003), and the 1962 U.S. Starfish Prime test, which produced a nuclear electromagnetic pulse that damaged civil infrastructure in Hawaii (Savage et al. 2010). However, these exceptions are small in scale relative to the damage of Hiroshima and Nagasaki, let alone relative to the potential damage from a larger nuclear war, which limits the insight they offer.

There have been a variety of attempts to characterize the impacts of a new nuclear war. Early studies include Ikle (1958) and Wigner 1969). The U.S. Office of Technology Assessment published a detailed study on the human impacts of a Soviet Union-U.S. nuclear war, finding "that conditions would continue to get worse for some time after a nuclear war ended, and that the effects of nuclear war that cannot be calculated in advance are at least as important as those which analysts attempt to quantify (OTA 1979, p.iii)." Shortly after, a team of natural scientists published research on a global environmental effect they called nuclear winter (Turco et al. 1983); this line of research continues to this day (Mills et al. 2014) and has been used to model agriculture declines (Xia et al. 2015). There have also been studies of the economic (e.g., Cantor et al. 1989) and humanitarian (e.g., Fihn 2013) consequences of nuclear war.

A general conclusion from this research is that the human impacts are considerably more uncertain than the physical impacts, though even the latter are uncertain (Frankel et al. 2013). Hanson (2008) makes similar statements about the relative importance of indirect societal dynamics as compared with direct physical effects of any large-scale disaster, including nuclear war. Overall, there is a wide span of opinion in the literature about how well humans would fare after nuclear war, ranging from relative optimism (e.g., Kahn 1960), to dark-ages scenarios (e.g., Peterson 1983), all the way to the possibility of human extinction (e.g., Sagan 1983).

Despite all this prior research in the impacts of nuclear war, there is relatively little research modeling or quantifying the total impacts for purposes of risk analysis. Toon et al. (2007) models a range of effects including local fatalities (based on Hiroshima and Nagasaki data), radiation exposure, and smoke emissions (the causal mechanism of nuclear winter and related environmental effects). Helfand (2013) estimates the total famine risk in a nuclear war scenario based on models of agriculture decline from nuclear winter. Baum (2015) estimates a threshold of nuclear weapons likely to result in global catastrophe from nuclear winter. However, to the best of our knowledge, there have been no prior attempts to model the total impacts of nuclear war.

This lack of relevant prior research derives from a broader neglect of the human impacts of nuclear war. One recent review puts it as follows: "The number of studies [on infrastructure and human impacts] is relatively modest, and many of them are 'case studies' limited to analyzing the effects on one or two cities. Simply stated, negligibly small resources—compared to the investment in understanding the physical effects of nuclear weapons—have been devoted over the years to understanding these non-physical consequences" (Frankel et al. 2013, p.23). The current paper aspires to make the most out of what limited prior research is available. However, a robust literature on the human impacts of nuclear would make the modeling task much more productive.

Background

This paper focuses on the impacts of nuclear war, which we define as an event in which one state attacks another state with nuclear weapons. This definition excludes nuclear terrorism and other attacks by nonstate actors. It also excludes events involving accidental nuclear detonations. However, the impacts are largely the same regardless of whether a detonation is from interstate war, nonstate actors, or accident. The main difference is that nuclear wars are likely to be much larger than nuclear attacks by nonstate actors or accidental nuclear detonations, but each type of event still has many of the same impacts, just at different scales.

There are two reasons to model the impacts of something: to produce impact estimates and to develop a better understanding. Impacts estimates are important for making certain types of decisions, such as how much to prioritize nuclear war risk relative to other risks. Understanding nuclear war can be at least as important for figuring out what actions can reduce the risk. This paper works towards impacts estimates, but it is largely oriented towards an improved understanding of nuclear war. To that effect, this section provides some general background on nuclear war impacts modeling.

Which Impacts Matter?

Nuclear war has many different types of impacts: physical impacts, such as the blast wave and ionizing radiation released in nuclear detonations; ecological impacts, such as the absorption of radiation by plants and animals; medical impacts, such as burns from fires caused by detonations; economic impacts, such as the destruction of manufacturing facilities; political impacts, such as the death of political leadership; cultural impacts, such as the fear of additional nuclear attacks; and more.

In order to focus attention, it is important to consider which impacts matter most. The relative importance of different types of impacts is largely a moral question. There are longstanding debates on such matters as how much to value ecological impacts (e.g., Devall 2001), harms to non-human animals (e.g., Singer 1985), various health and quality of life impairments (e.g., Prieto and Sacristán 2003), people in distant places (e.g., Smith 1998), and members of future generations (e.g., Laslett and Fishkin, 1992). Details of these debates and how they might be resolved are beyond the scope of this paper.

This paper focuses on the impacts of nuclear war on humans. All human lives are valued equally, regardless of their geographic location, membership in a present or future generation, or any other factor (wealth, nationality, gender, religion, ethnicity, etc.). In focusing on human impacts, we do not mean to argue that only human impacts are important. Modeling and quantifying the impacts of nuclear war on such things as ecosystems and nonhuman animals would also be valuable, but is beyond the scope of this paper. More precisely, this paper values human impacts intrinsically, meaning that human impacts are valued for their own sake. Impacts on other things such as ecosystems are valued instrumentally, meaning they are valued to the extent that they affect humans (e.g., Baum 2012).

An important consideration in this paper is the possibility of nuclear war resulting in a global catastrophe. In general terms, a global catastrophe is generally understood to be a major harm to global human civilization. Some studies have focused on catastrophes resulting in human extinction, including early discussions of nuclear winter (Sagan 1983). Several studies posit minimum damage thresholds such as the death of 10% of the human population (Cotton-Barratt et al. 2016), the death of 25% of the human population (Atkinson 1999), or 10^4 to 10^7 deaths or $\$10^9$ to $\$10^{12}$ in damages (Bostrom and Ćirković 2008). Other studies define global catastrophe as an event that exceeds the resilience of global human civilization, resulting in its collapse (Maher and Baum 2013; Baum and Handoh 2014).

A case can be made for focusing on catastrophes causing permanent harm to human civilization. If members of future generations are counted equally, then permanent harm would be an especially large impact, due to the potentially large number of people in future generations. Early studies of this idea focused on human extinction, which is clearly a permanent harm (e.g., Sagan 1983; Parfit 1984). More recent scholarship recognizes that comparable permanent harm can come from the permanent collapse of human civilization or other long-term declines (e.g., Bostrom 2002; Maher and Baum 2013). The potential for nuclear war to cause either type of permanent harm is an important question, which this paper will consider in some detail.

Uncertainty About Impacts

The risk of nuclear war is full of uncertainty. There are two core reasons why. One reason is that nuclear war is (fortunately) rare. There has been only one nuclear war (WWII) in the seventy-three year history of nuclear weapons. This means there is relatively little information available to reduce uncertainty about the risk. The other reason is that nuclear war is complex. Nuclear war can destroy cities, disrupt the global economy and the global environment, change international norms and geopolitical balances, and more. It is extremely difficult or perhaps even impossible to predict in advance what all these impacts will look like, especially with so little historical precedent. Analysis of nuclear war impacts should avoid making unjustified claims and instead defer to the considerable uncertainty.

There are two types of uncertainty about the impacts of nuclear war. One is uncertainty about what type of nuclear war(s) will occur. Possible nuclear war scenarios vary in terms of which states are involved, how many nuclear weapons are used, and what locations are targeted in nuclear attacks, among other factors. The other is uncertainty about what impacts will result from a given nuclear war scenario. As noted above, the physical impacts of nuclear war are uncertain and the human impacts are even more uncertain (Frankel et al. 2013).

A complete accounting of the possible impacts of nuclear war would include the full range of possible nuclear war scenarios as well as the full range of possible impacts from a given scenario. Unfortunately, that is not a tractable task. There are countless possible scenarios and impacts. Some key details are classified, including details about nuclear weapons targets (affecting scenarios) and about the ways in which military facilities are protected from nuclear attacks (affecting impacts). Other key details hinge on complex and/or poorly documented phenomena, such as the rate at which nuclear weapons operators obey launch commands (affecting scenarios) and the resilience of the global economy to nuclear war (affecting impacts).

This extensive uncertainty creates a challenge for efforts to model and quantify the impacts of nuclear war. Any model will inevitably only include some portion of the possible scenarios and the possible impacts from a scenario. Furthermore, any model attempting to include a large portion of the detail would quickly become exceedingly large. Fortunately, accounting for the full detail is not the only goal of modeling. A model can be useful if it accounts for key features and/or illustrates what the full detail might look like. That is the aim of the model presented in this paper. The model includes key features of nuclear war scenarios and impacts as well as some smaller details to illustrate what the full detail might look like.

Nuclear War Scenarios

Nuclear war could occur between a range of states, for a range of reasons, and in a range of ways. This section focuses on the ways in which nuclear war is conducted. That is, what does a particular nuclear war look like? The focus is exclusively on the use of nuclear weapons. Other military activities are not considered. Why the nuclear war occurred is also not considered here; this is an important question but is best reserved for analysis of the probability of nuclear war. While it is not possible to account for all details of nuclear war scenarios, what follows are some core features.

Number Of Detonations

The number of nuclear detonations that occur in a nuclear war is perhaps the most commonly used metric for the severity of the war's impacts. All else being equal, the more nuclear weapons are detonated in a nuclear war, the more severe the impacts will be. The number of detonations is thus a quick, simple number that clearly distinguishes between a small nuclear war, such as a war in which Israel uses one or a small handful of nuclear weapons against one of its non-nuclear-armed adversaries, a medium-sized nuclear war, such as a war in which India and Pakistan use tens to low-hundreds of nuclear weapons, and a large nuclear war, such as a war in which Russia and the U.S. use high-hundreds to thousands of nuclear weapons.

At the time of this writing, there are around 14,550 nuclear weapons in the world (Kristensen and Norris 2017). This is down from the Cold War peak of over 70,000. Over 90% of the current nuclear weapons are possessed by Russia and the U.S. The other nuclear-armed states are China, France, India, Israel, North Korea, Pakistan, and the United Kingdom. North Korea has the smallest nuclear arsenal and may not have any that it can deliver to wartime targets. The other states' arsenals range from around 80 (Israel) to around 300 (France). Most of the nuclear weapons are in military stockpiles and are not available for immediate use. Only France, Russia, the U.K., and the U.S. keep nuclear weapons (about 4,000 total) in permanent deployment available for use at any time (Kristensen and Norris 2017).

The number of nuclear weapons detonated in a war depends on several factors. First is which states participate in the war. A war involving Russia and/or the U.S. could have a much larger number of nuclear weapons than a war that involves only the other nuclear-armed states. However, participating states would not necessarily use all of their nuclear weapons. For example, Russian military doctrine includes the concept of a "de-escalatory nuclear strike" that is intended to end a war without large-scale nuclear exchange (Sokov 2014). Or, in a nuclear war between North Korea and the U.S., the U.S. is virtually guaranteed to not use more than a small fraction of its arsenal, simply due to a lack of targets in North Korea.

Even if a participating state wanted to use its entire arsenal, it might not be able to. Some weapons could malfunction, failing to launch or detonate. Others could be destroyed by the other side. Indeed, the opponent's nuclear arsenal could be a primary target of nuclear attacks. Nuclear weapons and/or their delivery vehicles (generally airplanes or missiles) could also be destroyed by attacks with conventional weapons or by air or missile defense systems. Missile defense systems are of dubious reliability, but they may nonetheless be able to thwart at least some incoming nuclear attacks. The net effect is that a state could lose some portion of its nuclear arsenal during the course of a war. How large that portion is depends on the other side's ability to attack it. One study found that the U.S. may be able to threaten the entire Chinese or Russian arsenals (Lieber and Press 2006).

The severity of nuclear war generally increases with the number of nuclear weapons. However, the increase in severity would generally probably not be proportionate to the increase in number. In many cases, using twice as many nuclear weapons would produce less than twice the impacts. The main reason for this is that the most important targets are likely to be destroyed by the first detonations. For example, in WWII, Hiroshima and Nagasaki were targeted for nuclear bombings because larger cities like Tokyo had already been destroyed in attacks with other weapons. More recent nuclear war plans often call for "overkill" in which multiple weapons are launched at the same target in order to ensure the target's destruction (Rosenberg 1983).

In some nuclear war scenarios, doubling the number of detonations can more-than-double the severity of the impacts. This can occur, for example, if a "de-escalatory" nuclear strike fails to deter subsequent escalation. Russian plans for de-escalatory nuclear strikes tend to target airbases, aircraft carriers, and other military installations. If de-escalation fails, and in particular if the initial nuclear attack leads to a larger nuclear exchange, then subsequent nuclear detonations could target cities. It is even possible that smaller cities would be targeted first. A policy of gradually increasing target size would be consistent with the philosophy of de-escalation. In this case, increasing the number would cause an even greater increase in severity.

Weapon Design

Not all nuclear weapons are created equally. Different weapon designs can lead to significantly different impacts. Perhaps the most important design variable is yield. A nuclear weapon's yield is the amount of energy it releases, generally measured in units of tons of TNT equivalent. For example, the bomb dropped on Hiroshima was around 15 kilotons TNT equivalent (KT), while the Nagasaki bomb was around 20KT. The largest nuclear detonation ever was the Tsar Bomba, which the Soviet Union detonated in a test in 1961. Its yield was 50,000KT or 50 megatons (MT).

The damage caused by a nuclear detonation generally increases with yield. The relation is less-than-linear: a detonation with twice the yield will cause less than twice the damage. The energy released in a detonation is concentrated at the point of detonation. A higher-yield detonation will cause a greater perturbation to its immediate vicinity. However, even a small detonation will destroy the immediate vicinity. Destroying it more with a high-yield detonation makes no difference to the total severity of the detonation. A portion of the detonation's energy is wasted. Larger yields have higher portions of energy wasted.

How the yield is packaged is also an important design attribute. Nuclear weapons can have hohlraums (radiation cases) of varying thickness. A typical nuclear weapon has a thick hohlraum in order to maximize the explosive force. In contrast, a neutron bomb has a thin hohlraum in order to maximize the amount of ionizing radiation released (Miettinen 1977). The impacts of neutron bombs would mainly be to human bodies (and other biological organisms) in the vicinity of the detonation. Damage to physical infrastructure would be minimal.

Another design variable is the weapon's external case, which can be hardened and shaped to enable the weapon to penetrate underground. These weapons are commonly known as "bunker busters". Compared to a weapon of the same yield that cannot penetrate underground, a bunker buster creates a much larger seismic force (Nelson 2003). Bunker busters are intended to destroy hardened underground targets. The impact of these weapons thus depends on what the targets are.

Detonation Location

The impacts of a detonation depend heavily on the location at which the detonation occurs. The detonation location is a point in three-dimensional space (latitude, longitude, altitude) and a point in time. All four of dimensions are essential to the impacts of a detonation. The importance of location is seen, for example, in the fact that more people died from the two nuclear detonations at Hiroshima and Nagasaki than from the 2,000 test detonations that have been conducted, even though many test detonations were of much higher yield. The reason for this is simply that the test detonations all occurred in locations isolated from large human populations. Here we review three key environmental attributes of locations (altitude, topography, and weather) and two key societal attributes (population density and infrastructure design).

Altitude. Nuclear weapon detonation altitudes can range from underground or underwater to surface or near-surface to high-altitude locations. Underground detonations create large seismic forces that can threaten nearby built infrastructure, including underground facilities, as in the above discussion of the bunker buster nuclear weapon design. Underwater detonations create waves and a dome of spray. Deeper detonations transfer more energy to the water resulting in larger waves and smaller spray domes. Above-ground detonations at low altitudes create a large blast of air that can destroy buildings and other built infrastructure and also cause extensive human casualties. High-altitude detonations create a large electromagnetic pulse that can destroy electronic equipment but causes no direct harm to human bodies and no structural damage to built infrastructure. Each of these altitudes results in different types of impacts (Frankel et al. 2013).

In a nuclear war, most detonations are likely to be at low altitude, because this causes the most damage to military and civilian targets. High-altitude detonations could be used in order to damage the target state's communications, military, industry, and other systems dependent on electronics. However, a single high-altitude detonation could cover a large portion of a continent, so at most only a small number of high-altitude detonations would be needed. Underground detonations would likely be much less numerous because they target specific underground facilities, which are much less numerous than above-ground targets. The range of situations in which underwater locations would be targeted is similarly small.

Topography. For low-altitude detonations, damage is more extensive in locations with flat topography. This is because hills and other topographic features can shield from the effects of detonations. Hilly topography is one reason why fewer people died from the atomic bombing of Nagasaki, even though it was hit with a higher-yield weapon than Hiroshima (Toon et al. 2007).

Weather. For low-altitude detonations, damage is different and likely more extensive if the detonation occurs during dry weather. This is because rain, other precipitation, or humidity can dampen the effects of thermal radiation, resulting in less fire. The relatively dry conditions in Hiroshima led to it experiencing a firestorm, whereas Nagasaki did not. However, rainfall also concentrates a detonation's ionizing radiation in a smaller location, which can result in increased harm (Toon et al. 2007).

Population density. The more people are in the vicinity of a nuclear detonation, the more casualties are likely to occur, simply because more people are exposed to the physical effects of the detonation. This holds across altitudes. For underground detonations, higher population density means more people harmed by the seismic forces. For underwater detonations, it means more people exposed to radioactive water spray. For low-altitude detonations, it means more people harmed by direct exposure to the detonation as well as more building material to feed fires. For high-altitude detonations, it means more people who could lose their electronic infrastructure.

The population density of the detonation location largely depends on the military purpose of the attack. Nuclear attacks typically target either military installations ("counterforce" attacks) or industrial or population centers ("countervalue" attacks). Countervalue targets typically but not always have higher population densities. Exceptions include military targets located in population centers, including political leadership residing in national capitals, and industrial centers located outside major cities.

The time of detonation is important for population density. Many cities have higher population densities during the day because residents commute into work from suburbs. Most (but not all) cities and other target locations have population densities that gradually grow over the years, due to general population growth. However, during a war, population density can decrease dramatically if soldiers are drafted or if cities are evacuated or attacked. In "overkill" targeting of multiple nuclear weapons at one location, the first detonation will have much greater impact than the others.

Infrastructure design. The human impacts of nuclear detonations can vary considerably depending on how infrastructure is designed. Building materials vary in terms of their structural integrity (ability to withstand airblast and seismic force), their flammability, and the opacity of the smoke produced if they do catch fire (affecting the severity of nuclear winter). Electronics infrastructure can be shielded to avoid being damaged by an electromagnetic pulse. Fallout shelters can protect people from ionizing radiation. Well-designed infrastructure can offset some of the effects of population density: population centers tend to have stronger building materials and can also have economies of scale for fallout shelters, electronics shielding, and other measures. Finally, in the extreme case, isolated refuges can protect small populations even when general conditions are bleak (Baum et al. 2015a).

Details, Details, Details

The preceding discussion presents some general trends in nuclear war scenarios. However, the total effects of nuclear detonations and nuclear war can be highly sensitive to a wide range of details, even some seemingly small ones. For comparison, it is conceivable that, had nuclear weapons not been detonated at Hiroshima and Nagasaki, the Cold War would have proceeded differently. Indeed, it may not have stayed cold were it not for the vivid image of what a nuclear war could entail provided by Hiroshima and Nagasaki. Of course, one cannot know what would have happened in that counterfactual world, but the enduring norm against nuclear weapons is considered part of the "legacy of Hiroshima" (Schelling 2006). Or, to take a seemingly small detail that no one knew at the time, the long-term effects of World War I turned out to be highly sensitive to the fact that a German soldier named Adolf Hitler happened to survive several years of trench warfare (Lebow 2015).

Some details cannot be analyzed in advance. Hitler during WWI is a classic example. Diligent analysts working circa 1910 or 1915 could have used all of their imagination and still would be forgiven if thoughts like the Holocaust had never crossed their minds. To some extent, Germany's post-WWI receptiveness to Hitler's message was predictable, or at least it would be today given contemporary research on the role of humiliation in motivating violence (e.g., Lindner 2002). Regardless, plenty of important details can be analyzed in advance, and these can alter much of the above discussion about the impacts of nuclear detonations and nuclear war.

Take for example the debate over underground detonations with nuclear bunker buster weapons. Advocates of these weapons point to the possibility of them destroying underground facilities for weapons of mass destruction (WMD) or other dangers. Critics, on the other hand, worry that the weapons diminish the norm against nuclear weapons use, thereby increasing the risk of nuclear war with larger numbers and higher yields of nuclear weapons (Nelson 2003). Both sides of the debate make fair points. If a bunker buster destroys a WMD facility, its detonation could be saving many lives, far more than the number of casualties in the attack. On the other hand, if the use of nuclear bunker busters leads to more nuclear weapons use in any present or future conflict, that could overshadow any other impacts.

These sorts of details can be entirely specific to the nuclear war or nuclear detonation in question. Therefore, the impacts of nuclear war would ideally be analyzed on a case-by-case basis according to the particular details of each nuclear war scenario. Unfortunately, that is not feasible. Fortunately, many details are similar across some or all nuclear war scenarios. What follows is an attempt to chart out the impacts of nuclear war in a way that works across many different scenarios. One should nonetheless recognize that important details will still vary from scenario to scenario.

The Model

The model depicts impacts of nuclear detonations that occur in the context of a war. It can be used for nuclear wars involving any number of nuclear detonations. Nuclear wars with multiple nuclear detonations would run the model multiple times and sum up the total effect. For each model run, the weapon design and detonation location are input into the model and impacts on human lives are output from the model.

The model begins with a nuclear weapon detonation, then branches out to the initial effects of a detonation, then branches out further to include subsequent effects caused by the initial effects. For example, nuclear detonations produce thermal radiation, which can in turn cause fires. As the model branches out further and further, it includes more detail and more long-term effects of nuclear detonations. In principle, with enough branches, the model could include all possible effects. In practice, there is unlimited detail that could be modeled and so only a selection of the effects can be shown.

The model contains many different types of impacts, not all of which would occur in a particular nuclear war scenario. Some types of impacts require certain types of detonations that would not occur in some scenarios. For example, impacts caused by water displacement are unique to underwater detonations, yet many nuclear war scenarios would not involve any underwater detonations. Some types of impacts are uncertain and may not occur in any scenario. For example, it has been proposed that nuclear wars could disrupt a proposed environmental protection activity known as geoengineering (Baum et al. 2013). However, geoengineering is not currently being conducted, may never be conducted, or may not be disrupted by nuclear war. Therefore, this model should be interpreted as covering a range of potential impacts of a range of potential nuclear wars. It likewise follows that using this model to estimate the total impacts of a nuclear war requires knowing the details of the nuclear war scenario. Different nuclear wars will have different impacts.

Figure 2 shows the first round of branching: the detonation and the initial effects. There are five main model branches, corresponding to five initial effects:

(1) *Thermal radiation* is electromagnetic radiation, mainly in the visible and near-visible frequencies. Thermal radiation is a concern mainly for surface and low-altitude detonations.

(2) *Blast* is a large increase in pressure coming from the explosion. Depending on where the detonation occurs, the blast can be an increase in air pressure (“airblast”), an earthquake-like movement of the ground (“groundshock”), or a displacement of water.

(3) *Ionizing radiation* is high-energy particles and electromagnetic radiation that can free electrons from atoms and molecules. Ionizing radiation is a concern mainly for underwater, surface, and low-altitude detonations.

(4) *Electromagnetic pulse* is an electromagnetic field generated from high-altitude nuclear detonations.

(5) *Human perceptions* are the thoughts and reactions that humans have to the occurrence of a nuclear detonation.

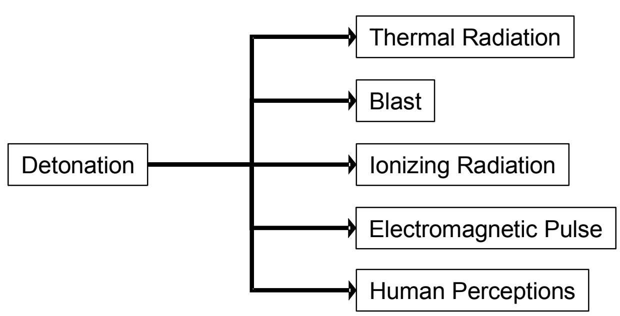

Figure 2. Initial effects of nuclear weapons detonations.

The paper below provides details on the five main model branches. Each branch is discussed in turn, followed by discussion of several “modules”. The modules are chunks of model that are used in several parts of the model. For example, thermal radiation and blast can both cause fire. The effects of the fire are similar for both causes. It is more concise to present one fire module instead of repeating the same details in both model branches. Modules can also connect to each other. In some cases, two modules connect back and forth to each other, creating a loop. For example, fire damages infrastructure, which can in turn lead to more or less fire, depending on the details.

For readers familiar with computer programming, the model modules may be reminiscent of modular and object-oriented programming. This is by design. This paper only provides the general model structure, not all the mathematical details needed to convert the model to code. Those details would include the mathematical relationships between the five main types of nuclear detonation effects (Figure 2) and all the subsequent model details (shown below). Such detail is well beyond the scope of this paper. It is hoped that future work will provide this detail, in which case code can be written. That would provide even more insight into the impacts of nuclear war.

Model details draw from a wide range of sources. Several sources were especially helpful in building the model, in particular OTA (1979), EMP Commission (2008), and Frankel et al. (2013). The EMP Commission report is especially valuable for its detailed accounting of impacts on interconnected infrastructure systems. While the report focused on electromagnetic pulse impacts, its insights are more widely applicable. Prior modeling of the impacts of nuclear war have focused mainly on immediate damage near the detonation and food insecurity from nuclear winter (e.g., Toon et al. 2007; Helfand 2013). Modeling the impacts of nuclear war on infrastructure has been a weakness of the literature and is an important contribution of this paper.

Branch: Thermal Radiation

Thermal radiation is, along with some ionizing radiation, the first effect of nuclear detonations to be experienced. It travels at the speed of light to points within eyeshot of the detonation. OTA (1979, p.20) likens the thermal blast from nuclear detonations to "a 2-second flash from an enormous sunlamp". As shown in Figure 3, thermal radiation can also cause harm via direct exposure to human bodies and via exposure to buildings.

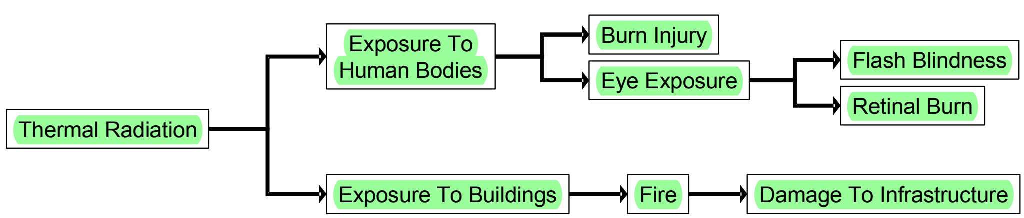

Figure 3. Effects of thermal radiation from nuclear weapons detonations.

The exposure of thermal radiation to human bodies can cause burn injuries and eye damage including flash blindness and retinal burn. Burn severity decreases with distance from the detonation. OTA (1979, p.21) reports that a 1MT detonation can cause first-degree (mild) burns up to seven miles away and third-degree (severe) burns up to five miles away, with potential fatalities from a single detonation over 10,000. Flash blindness is more prevalent than retinal burn but it is only a temporary effect, though it can cause more permanent harms such as via car crashes.

The exposure of thermal radiation to buildings can cause fire if the radiation passes through ignitable materials such as beds and furniture. Details of the impacts of the fire are shown below in the fire module.

Branch: Blast

Blast can disrupt air, ground, or water. It can cause human impacts in three main ways, corresponding to the three branches of the blast model shown in Figure 4.

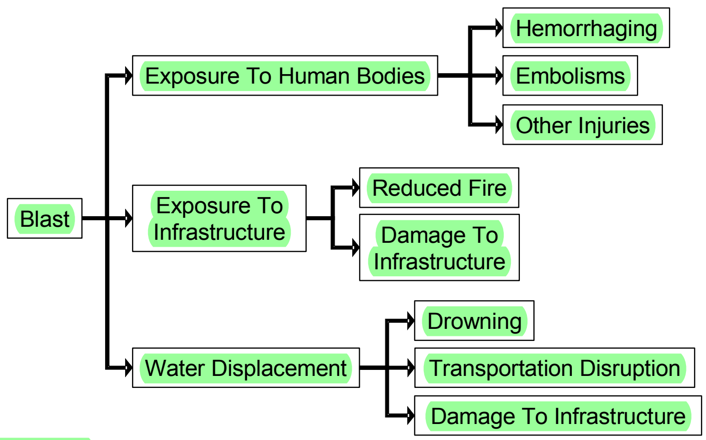

Figure 4. Effects of blast from nuclear weapons detonations.

The first impact of blast comes from direct exposure to human bodies. This occurs mainly from surface or low-altitude detonations. The blast can cause bodily harm in several ways, including hemorrhaging and embolisms (Phillips 1986; Argyros 1997).

The second impact of blast comes from exposure to infrastructure. This occurs with underground, surface, or low-altitude detonations. For surface and low-altitude detonations, one immediate effect of blast can be to extinguish some fires caused by thermal radiation. This effect reduces the impacts of fire as per the fire module. The blast can also cause extensive damage to infrastructure. For some detonations, such as underground detonations of low-yield nuclear bunker busters, damage to infrastructure is the primary intended effect. Infrastructure exposed to blast can be damaged if the blast is strong enough and the infrastructure is not resilient to it. Details of the damage are presented in the damage to infrastructure module.

The third impact of blast comes from water displacement. This occurs with underwater detonations. Such detonations may be relatively uncommon during nuclear wars, but they can nonetheless have large impacts. As one data point, the U.S. detonated a 21KT nuclear weapon 90 feet below the surface in the 1946 "Baker" test. This sent water 900 feet into the air (Frankel et al. 2013). While the Baker test was in a remote Pacific location, a similar detonation near a major coastal city could cause extensive damage. Some people could drown in the ensuing floods. The water could also disrupt both marine and land transportation, as shown in the transportation disruption module. The flooding would also damage infrastructure, as shown in the damage to infrastructure module. The water can also cause damage by bringing extensive ionizing radiation into populated areas; these damages are covered in the ionizing radiation section of the model.

One impact of blast not shown in Figure 4 is cratering, which is the formation of craters in Earth's surface. This occurs from detonations on or near the surface (OTA 1979). Cratering is not modeled because the human impacts of cratering are not significant, especially relative to other effects of nuclear detonations, including other effects of blast.

Branch: Ionizing Radiation

Direct exposure to ionizing radiation can cause harms (and possibly some benefits) to the bodies of humans and other biological species, as well as to infrastructure. The first three branches of Figure 5 show the medical, ecological, and physical effects of direct exposure to ionizing radiation. The fourth branch of Figure 5 covers human perceptions. Ionizing radiation is controversial and commonly misunderstood, often provoking highly consequential human actions.

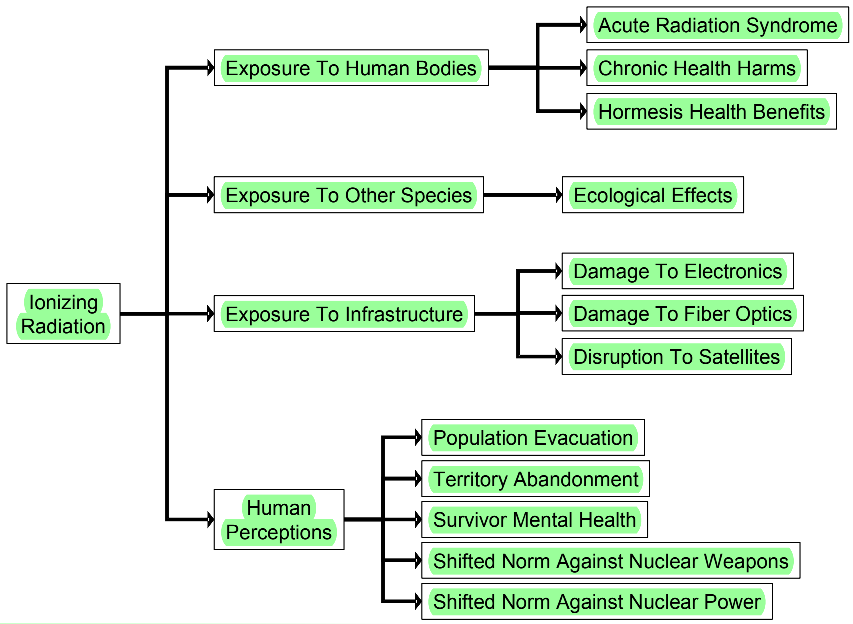

Figure 5. Effects of ionizing radiation from nuclear weapons detonations.

Ionizing radiation affects human bodies by displacing electrons from the bodies' atoms and molecules: it "knocks our electrons off". Ionizing radiation occurs across the planet from natural and artificial sources. This background exposure to ionizing radiation is in low doses, which is why humans exposed to it can still live full lives. The medical effects of ionizing radiation depend heavily on the dose. In toxicology this is known as the dose-response curve. The shape of the ionizing radiation dose-response curve is a matter of ongoing and often passionate scholarly debate (e.g., Brenner et al. 2003; Sanders 2010; Scott and Dobrzyński 2012).

High doses of ionizing radiation are clearly harmful. The effects are well-documented. Much of the data comes from Hiroshima and Nagasaki victims, the interpretation of which is also debated (e.g., Ozasa et al. 2011; Doss et al. 2012). The large effects that come from high doses are relatively easy to study because the effects stand out clearly relative to other environmental exposures and medical effects that a person can accrue over the years.

At high doses, the severity of the harm increases with the size of the dose. At the highest doses, the effect is called acute radiation syndrome. Symptoms include nausea, vomiting, bleeding, and brain damage. Death can occur in a few days to a few months depending on the dosage. Acute radiation syndrome is believed to have caused about a third of total deaths from the bombings of Hiroshima and Nagasaki (Finch 1987). At more moderate doses, ionizing radiation can cause chronic health problems. One effect is called chronic radiation syndrome (Akleyev 2014). Moderate doses of ionizing radiation can also cause cancer. Cancer is not guaranteed to occur; the ionizing radiation only increases the probability of any given person getting cancer. Furthermore, the onset of cancer can be significantly delayed. The person could live a relatively normal life for years or even decades before the cancer develops.

For low doses, the effects less clear and highly disputed (e.g., Brenner et al. 2003; Sanders 2010; Scott and Dobrzyński 2012). Low doses may be either harmful, neutral, or beneficial, depending on the dose and the dose-response model used to analyze it. Two competing models predict different low-dose effects (Figure 6). The linear no-threshold model predicts some harms all the way down to zero dose. The size of the harm is in linear proportion to the size of the dose. The hormesis model predicts that below some dose threshold, the response is less harmful than the linear no-threshold model predicts. At the lowest doses, health benefits are predicted. For comparison, hormesis curves are found with food and water: one must eat and drink a certain amount to be healthy, but larger doses can bring illness and even death. For ionizing radiation, determining the actual response to low doses is difficult because the effects are small and hard to distinguish from effects caused by other factors.

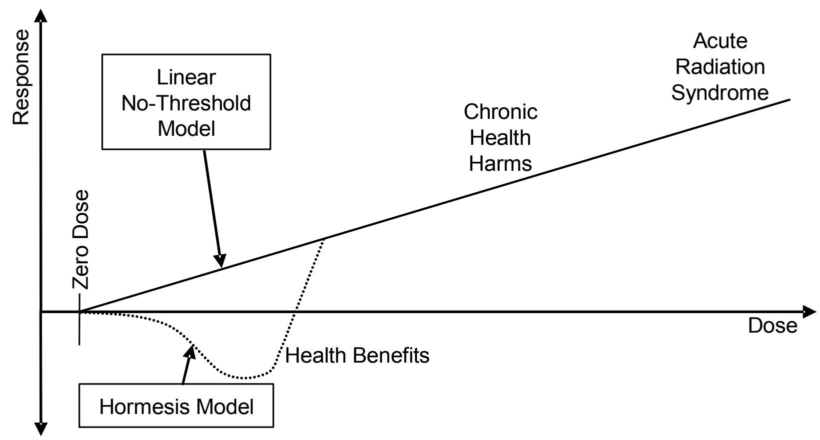

Figure 6. Illustrative sketch of the linear no-threshold model and hormesis model of the medical effects of ionizing radiation. Figure details may not be drawn to scale.

Nuclear detonations can cause the full range of ionizing radiation doses. People near the detonation can get acute radiation syndrome, though people nearest to the detonation would typically be killed faster by thermal radiation and/or blast effects. People further away from the detonation can get doses associated with hormesis benefits or a small possibility of harms under the linear no-threshold model. Which people get which doses depends on weapon design, detonation location, wind speed and direction, precipitation, and other factors. Hiroshima and Nagasaki provide the only data points; estimates of cancer deaths range from 430 to 1,900 (Perrow 2013).

Ionizing radiation has similar effects on non-human species. Animals and plants alike can be harmed and die, with worse effects occurring at higher doses. Hormesis benefits have been observed in controlled studies with laboratory animals (Sanders 2010, chapter 14). The higher doses of ionizing radiation from nuclear detonations can cause significant agricultural disruption (modeled in the agriculture disruption module) and ecological harm. However, the harms are generally temporary: ecosystems can recover and flourish in the years or decades following a nuclear detonation. (The human environment can recover as well, as seen in the fact that Hiroshima and Nagasaki are flourishing cities today.)

Ionizing radiation can also affect built infrastructure. Specifically, it can damage electronics and fiber optic cables and (for high-altitude detonations) disrupt satellites (Frankel et al. 2013). These effects are generally small. Indeed, the satellite disruption lasts only a few minutes (Frankel et al. 2013). The effects thus make a small (possibly negligible) contribution to the overall damage to infrastructure as modeled in the damage to infrastructure module.

Finally, there are the effects of human perceptions of ionizing radiation. These are numerous, complex, and in many cases difficult to predict. A simple effect is the evacuation of populations located in areas perceived to be exposed to harmful doses of ionizing radiation. Evacuations are a standard procedure for such exposures, as seen most recently in the evacuation of the Fukushima region following the 2011 nuclear power plant accident. Evacuations are likely to occur following nuclear detonations to the extent that they are feasible. Depending on the details of the nuclear war scenario, evacuation could be rendered difficult, for example because of the death or incapacitation of people or damage to transportation systems.

Evacuations can lessen the harms caused by ionizing radiation by reducing a population's exposure. However, evacuations can also cause harms. One potential harm is by depriving populations of hormesis benefits, if there are any. Another harm comes from the evacuation itself. This was seen in the Fukushima evacuation, which caused an estimated 1,100 deaths, due mainly to fatigue and in part also due to collapsed medical infrastructure (Saji 2013). Suffice to say, evacuation during or after nuclear war would face considerably different circumstances.

Evacuated territory could be abandoned for an extended duration or even in perpetuity. While Hiroshima and Nagasaki have been repopulated, the Chernobyl area remains largely abandoned due to concerns about ionizing radiation. Abandoning territory has both economic and ecological effects. The economic effects derive from the loss of whatever geographic resources the abandoned territory offered and are thus site-specific. The ecological effects are generally positive, such as the ecological flourishing now found in the abandoned Chernobyl area (Mulvey 2006).

Perceptions of ionizing radiation can have a strong impact on the mental health of nuclear detonation survivors. Fear of ionizing radiation can lead to survivors being socially stigmatized (Peters et al. 2004) and can also lead to survivors having negative attitudes about themselves (e.g., low self-esteem). One recent study of Nagasaki survivors found poor mental health 50 years after the bombing, due mainly to fears about radiation (Kim et al. 2011). There are even some indicators of a radiation exposure causing an increase in suicide rates (Loganovsky 2007). There are some positives to speak of for nuclear detonation survivors. The Hiroshima and Nagasaki survivors—the *hibakusha*—have acquired a certain social status. This is seen in them being offered prominent speaking roles in major events about nuclear weapons (e.g., Thurlow 2014). Comparable opportunities are less available for other WWII survivors. However, the overall effect from perceptions of ionizing radiation appears to be a significant negative.

Perceptions of ionizing radiation also impact norms. These impacts are discussed in the shifted norms module.

Branch: Electromagnetic Pulse

Electromagnetic pulse causes no direct harm to human bodies and no direct structural damage to infrastructure. Instead, its primary effect is to damage electronics, which is modeled as a type of damage to infrastructure (Figure 7). A single high-altitude, high-yield nuclear detonation can damage electronics across an area as large as the continental U.S., with far-reaching consequences across the many sectors of society that are dependent on electronics (EMP Commission 2008). Details of the impacts are modeled in the damage to infrastructure module.

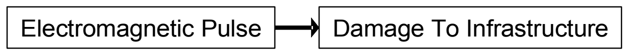

Figure 7. Effects of electromagnetic pulse from nuclear weapons detonations.

Branch: Human Perceptions

A nuclear detonation (or a broader nuclear war) would gain worldwide attention. People could react in many ways. These reactions could be very consequential, potentially even more consequential than the detonation/war itself. For comparison, many more people died in the Afghanistan and Iraq wars prompted by the 11 September 2001 attacks than died in the attacks themselves. The attacks also prompted many other actions, such as the creation of the U.S. Department of Homeland Security. WWII caused many major reactions, such as the creation of the United Nations. Human perception of a new nuclear war could cause similarly important effects, as shown in Figure 8.

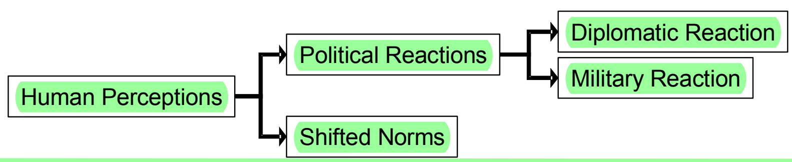

Figure 8. Effects of human perceptions of nuclear weapons detonations.

Nuclear war can cause several types of political reactions. Diplomatic reactions can include sanctions or changes of alliances. The international community has taken extensive diplomatic action against North Korea for building nuclear weapons, for example, and for Iran for developing capabilities that it could use to build nuclear weapons. If these or other countries were to use nuclear weapons in a war, the diplomatic actions could be even more intense.

It is possible for a nuclear war to prompt additional military action, including additional nuclear wars. Indeed, in the 1950s and 1960s, the international community worried that smaller nuclear-armed states could drag the larger ones into nuclear war in what was known as the “n+1 problem” (Ayson 2010). It is a matter of definition whether this should be considered one nuclear war or two. It would clearly be two separate nuclear wars if the first nuclear war prompted states not party to the war to acquire and subsequently use nuclear weapons. Those other states might be enticed by a perceived military value of nuclear weapons and a diminished norm against nuclear weapons. This is one of several norms that can be shifted by a nuclear war, which are detailed in the shifted norms module.

Module: Fire

Fire is an impact of several model branches and modules. The first is thermal radiation, which can cause fire very soon after a nuclear detonation. Soon after that, blast can reduce fire by extinguishing some of the fire caused by thermal radiation. Damage to infrastructure caused by blast and other effects can in turn cause fire by rupturing gas pipes and disturbing other sources of fire. Finally, water supply disruption and telecommunications disruption can impede firefighters’ ability to put fires out by denying them the tools they need to do their job.

The initial impacts of fire are shown in Figure 9. One impact is to damage infrastructure by burning more buildings. Other impacts come from the smoke lofted into the atmosphere by the fire. The smoke can disrupt air travel (Frankel et al. 2013), as modeled in the transportation disruption module. Some of the smoke can rise into the stratosphere (the second layer of the atmosphere, above the clouds), where it can spread worldwide and remain aloft for several years. While aloft, it can cause reduce stratospheric ozone (Mills et al. 2008; 2014) and block sunlight (Toon et al. 2007; Mills et al. 2014). Details of blocked sunlight are discussed in the blocked sunlight module.

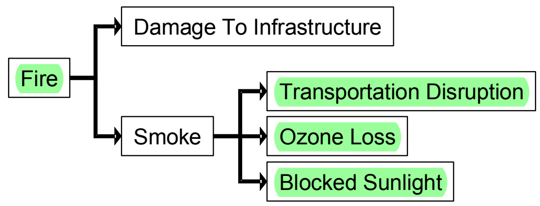

Figure 9. Effects of fire caused by nuclear weapons detonations.

Figure 10 shows impacts of ozone loss. Damage to the ozone layer allows more ultraviolet radiation to pass through the atmosphere and reach the surface. Increased ultraviolet radiation can cause a range of harms to humans including skin cancer, eye damage, and sunburn, as well as harms to both non-human animals and plants (Mills et al. 2008; 2014). Concerns about the health effects of exposure to ultraviolet radiation could potentially also reduce outdoor activity.

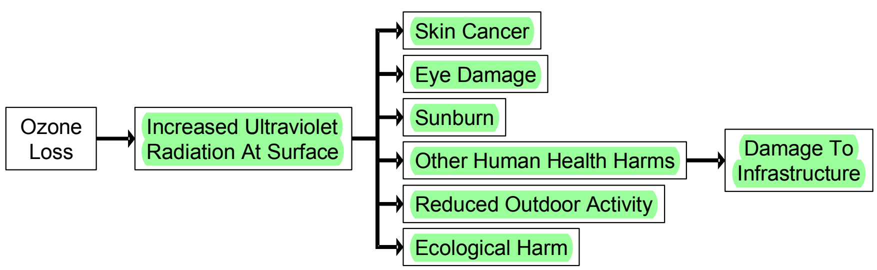

Figure 10. Effects of ozone loss caused by nuclear weapons detonations.

Hints of the reduction in outdoor activity can be seen today, especially in Australia, which has especially high exposure to ultraviolet radiation. The government of Victoria, Australia has encouraged outdoor workers to minimize their outdoor hours and use sunscreen, specifically citing workers in the construction, mining, and utilities sectors (Victoria 2005). Unfortunately, those sectors are among the most important for recovering from the damage to infrastructure caused by nuclear war, as discussed in the damage to infrastructure module. Outdoor workers tasked with repairing the damage may further lack access to sunscreen, due to disruption of sunscreen supply chains. Therefore, either the workers will be exposed to damaging ultraviolet radiation or their work will proceed more slowly.

Module: Blocked Sunlight

Fire caused by nuclear war can block sunlight by sending smoke into the atmosphere. The effect is strongest in the vicinity of the detonation shortly after the detonation occurs. Some smoke can also enter the stratosphere and block sunlight worldwide for many years. Furthermore, if nuclear war causes a general malfunction of society, this could potentially result in less sunlight being blocked due to the failure of intentional sun blocking known as geoengineering (Baum et al. 2013). Currently, no sunlight-blocking geoengineering is being performed, so any nuclear war would cause a net increase in the amount of sunlight being blocked (i.e., a net decrease in the amount of sunlight reaching the surface). If sunlight-blocking geoengineering is being performed when a future nuclear war occurs, the net effect would depend on the extent of fires caused by the nuclear war and the extent of the geoengineering. One important detail is that the sun-blocking particles in the stratosphere would fall out of the atmosphere in a few years, at which point temperatures would increase to wherever they would have been without the geoengineering (Matthews and Caldeira 2007) or nuclear war.

Figure 11 shows the initial impacts of blocked sunlight. Blockage of sunlight would reduce surface sunlight (i.e., the amount of sunlight reaching the surface), surface temperatures, and precipitation (due to less energy driving the hydrological cycle; see e.g. Mills et al. 2014). It can also shift wind patterns, though the net effect is unclear. Studies of global warming show that temperatures increase the fastest at the poles, which reduces air temperature differentials and in turn reduces wind (Ren 2010). The same logic suggests an increase in wind from blocked sunlight following nuclear war. Indeed, Mills et al. (2014) shows the largest post-nuclear-war temperature declines in high-latitude continental northern hemisphere and in the southern ocean, which would lead to increased temperature differentials. However, to our knowledge, the effect on wind has not been studied.

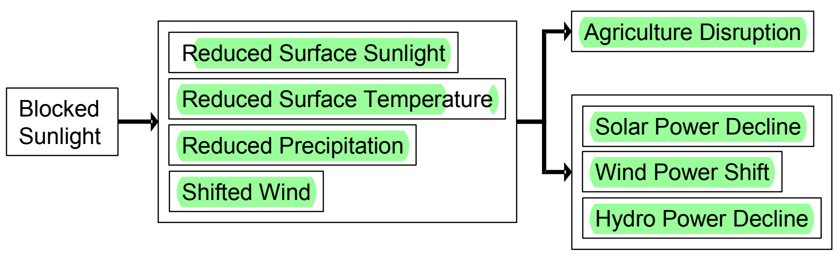

Figure 11. Effects of blocked sunlight caused by nuclear weapons detonations. The nested boxes are a visual convenience to reduce the number of arrows.

Reduced surface sunlight, surface temperature, and precipitation could in turn cause major disruptions to agriculture. For example, one recent study found that an India-Pakistan nuclear war could reduce China's rice crop by 29%, its maize crop by 20%, and its wheat crop by 53% (Xia et al. 2015). Another study found that an India-Pakistan nuclear war could put two billion people at risk of starvation (Helfand 2013). Details are discussed in the agriculture disruption module.

Reduced surface sunlight, surface temperature, and precipitation could also affect energy supplies. Specifically, reduced sunlight would cause a decline in solar power; reduced precipitation would cause a decline in hydroelectric power; and shifted wind would cause a shift in wind power. Figure 12 shows impacts of these effects. One impact is a disruption of energy supplies, details of which are discussed in the energy supply disruption module. Regions with heavy use of solar and hydroelectric power (e.g., Scandinavia) would be hit especially hard.

To make up for the losses of these power supplies, there might be an increase in fossil fuel, geothermal, and nuclear power generation. Most of the increase would probably come from fossil fuel, which can be scaled up relatively quickly. Geothermal power has relatively little potential to expand. Nuclear power expansion generally involves long construction times and could be further hindered if the nuclear war also strengthens the norm against nuclear power (see the shifted norms module). The net result would likely be an increase in greenhouse gas emissions. How this increase in greenhouse gas emissions compares to decreases caused by other nuclear war effects, to our knowledge, has not been studied and likely depends on the specifics of the nuclear war scenario.

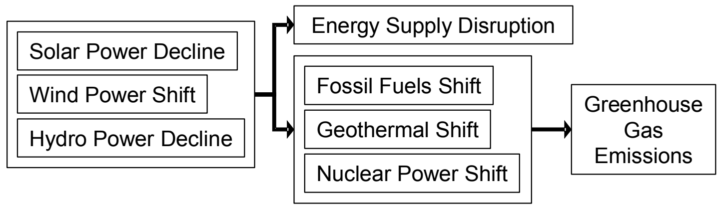

Figure 12. Effects of solar power decline, wind power decline, and hydroelectric power decline caused by nuclear weapons detonations. The nested boxes are a visual convenience to reduce the number of arrows.

Module: Damage To Infrastructure

Damage to infrastructure is a complex and important module. Different types of detonations could damage infrastructure across many sectors of society, as shown in Figure 13. Figure 13 may appear simple, with damage to infrastructure just branching out in several directions. However, each branch is itself a module. It is the job of the damage to infrastructure module to take the different types of inputs from different types of detonations and feed them into the modules. Details of this process are beyond the scope of this paper, but future work will benefit from careful attention to this.

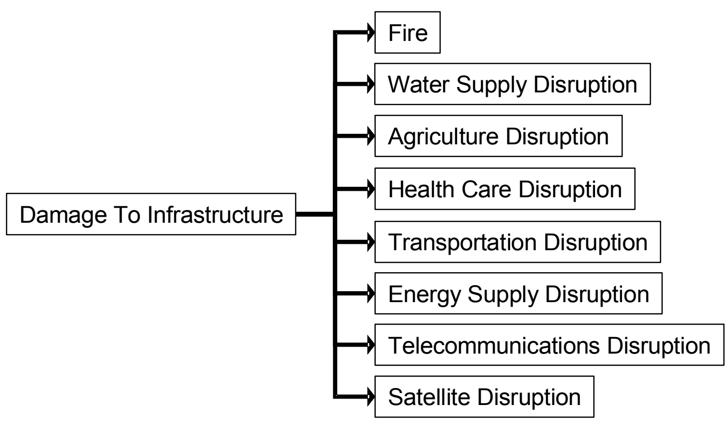

Figure 13. Effects of damage to infrastructure caused by nuclear weapons detonations.

A general outline of how the damage to infrastructure module functions can be seen from the various model inputs. Blast from surface or low-altitude detonations propagates through air, destroying buildings and other infrastructure. This can cause the full range of damage to infrastructure except satellite disruption. The effect on fire is especially significant. Damage to infrastructure causes fires by disrupting gas lines, stoves, and other combustibles and flammable materials (Frankel et al. 2013). In contrast, the effect on agriculture will be smaller and may even be zero for detonations in locations far from agricultural areas. These locations include some major urban and military targets. The impact on other sectors (water supply, health care, transportation, energy supply, and telecommunications) could depend heavily on detonation location. For example, a nuclear weapon detonated in Houston would likely have a larger impact on energy supply than a detonation in New York City because Houston is a major energy hub. The detonation in New York City would likely have a larger impact on transportation, because New York City is a major transportation hub.

Blast from underwater detonations can send large amounts of water to nearby locations, including coastal cities. This water could extinguish fires that may have been caused by other nuclear detonations. It can also cause a range of other damages. Details of the damages are poorly studied and poorly understood (Frankel et al. 2013). The potential for water displacement to cause extensive damage is seen in the effects of tsunamis. However, underwater detonations cause water displacement in significantly different ways than tsunamis.

Ionizing radiation and electromagnetic pulse can both damage electronics (Frankel et al. 2013). For ionizing radiation, the effect is small and local following surface or low-altitude detonations. For electromagnetic pulse, the effect is large and covering wide areas following high-altitude detonations. Electromagnetic pulse can cause extensive damage for all the module branches shown in Figure 13 except fire (EMP Commission 2008).

Finally, fire can damage infrastructure, which can in turn have a variety of effects, including more fire. The model's feedback loop between fire and damage to infrastructure serves as a basic fire model, i.e. a model of how fire and infrastructure (buildings, etc.) interact to determine fire patterns. Future work could incorporate a more advanced fire model including details such as building materials and weather conditions.

Much of the detail for the modules shown in Figure 13 comes from a report on the effects of an electromagnetic pulse commissioned by the U.S. government (EMP Commission 2008). The report details the impacts of a single high-yield, high-altitude nuclear detonation above the U.S. The report is perhaps the most detailed analysis available of the impacts of nuclear war on civil infrastructure, whether for electromagnetic pulse or other effects. While some of the impacts are specific to the U.S., many of them would occur for detonations above any country. Furthermore, other types of nuclear detonations (e.g., surface, low-altitude) can cause similar types of infrastructure disruptions. The details will be different, but much of the model structure is the same.

Module: Water Supply Disruption

Primary water supplies can be disrupted by several types of damage to infrastructure. Blast can destroy reservoirs, purification facilities, pipes, along with the sinks, showers, etc. that use the water. Fire can have a similar effect. Electromagnetic pulse can destroy pumps and other infrastructure required for purifying and transporting water (EMP Commission 2008). For smaller catastrophes, water supply is often a problem that is solved by transporting emergency water supplies (e.g., bottled water, water tank trucks) in from nearby, unharmed locations. However, for larger nuclear war scenarios, the affected area is too large for emergency water to be provided. Furthermore, if transportation systems are disrupted, then it may be more difficult to bring in emergency water.

Figure 14 shows potential impacts of water supply disruption. The most immediate is dehydration. Humans can survive without water for only about three days. When supplies are disrupted, seeking water quickly becomes an urgent priority. This in turn can lead to a labor shortage throughout the economy, as people spend their time seeking water. For comparison, many people throughout the developing world spend a large portion of their time procuring water instead of making more advanced economic and social contributions. If a sufficient portion of the population drops out of the labor pool, it can result in a wide range of problems, which are modeled in the general malfunction of society module. Additionally, in the absence of clean water, people may drink water from untreated sources, which can result in illness. Firefighters would also not have water available for fighting fires. Finally, under such dire conditions, law and order could deteriorate.

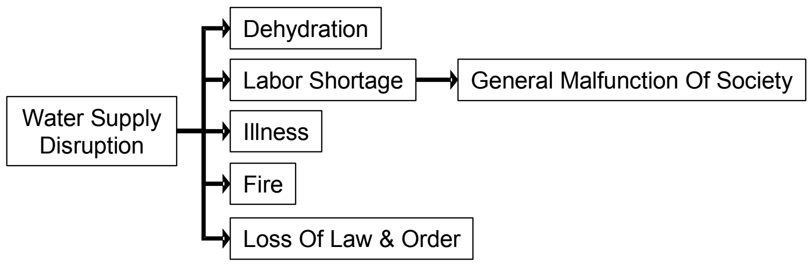

Figure 14. Effects of water supply disruption caused by nuclear weapons detonations.

Module: Agriculture Disruption

Nuclear war can disrupt agriculture in several ways. Blast can destroy agricultural sites. Blast and electromagnetic pulse can damage agricultural supply chains, from the sites where food is grown to where the food is processed and eventually sold. Concerns about ionizing radiation could cause agricultural from regions near detonations to be avoided, just as agriculture from Fukushima Prefecture has been avoided following the 2011 nuclear power plant accident (McMahon 2016). Finally, blocked sunlight (an effect of fires) can significantly reduce agricultural productivity worldwide (e.g., Helfand 2013; Xia et al. 2015).

Figure 15 shows potential impacts of agriculture disruption. When agriculture is disrupted, food availability decreases. When this happens, the first thing people generally do is consume stockpiled food. This includes personal stockpiles in their residences, ranging from whatever is in the kitchen to dedicated emergency food storage. It also includes institutional food stockpiles. However, for larger agricultural disruptions, currently available stockpiles would run out quickly (Baum et al. 2015b). This stockpile depletion can occur from blocked sunlight in larger nuclear war scenarios and potentially from other effects as well.

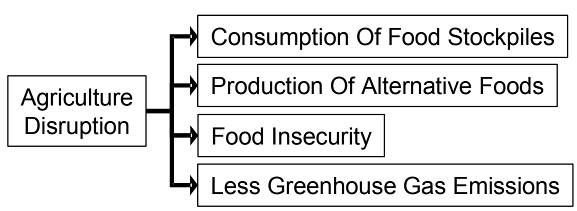

Figure 15. Effects of agriculture disruption caused by nuclear weapons detonations.

In the absence of adequate agriculture and/or food stockpiles, one option that has been proposed for food supply is “alternative foods” (Denkenberger and Pearce 2014; 2015). The foods are alternative in the sense that they derive their energy from sources other than the Sun, just as alternative energy derives from sources other than fossil fuels. Alternative foods include mushrooms grown on trees and bacteria grown on natural gas, both of which can be fed into the food supply. Denkenberger and Pearce (2014; 2015) find potential for alternative foods to serve as a large-scale food source even during extreme agriculture disruption. However, alternative foods technology is a new concept; societies have not yet taken the steps necessary to be able to scale up the technology in the event that they are needed. Alternative foods show promise, but they cannot yet be counted on.

If there food production and supply are inadequate, then there would be food insecurity. People who are already poor and malnourished would likely be hardest hit; many could face starvation (Helfand 2013). Details are described in the food insecurity module.

Finally, agriculture disruption would likely also reduce greenhouse gas emissions. Currently, the agriculture, forestry, and other land use sector causes about 25% of total greenhouse gas emissions (Smith et al. 2013). A significant disruption to agriculture could thus cause a major reduction in greenhouse gas emissions.

Module: Food Insecurity

In simple terms, food insecurity occurs when people do not have access to enough food. Nuclear war could cause food insecurity in two main ways: via agriculture disruption, causing a decline in the food supply, and via transportation systems disruption, causing a decline in the capacity to deliver food to the people who need it. Both disruptions can cause extensive food insecurity, with a range of impacts as shown in Figure 16.

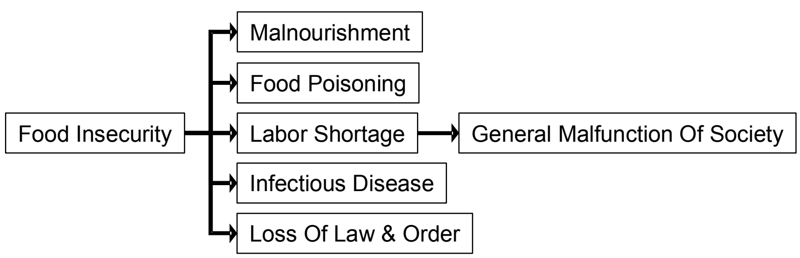

Figure 16. Effects of food insecurity caused by nuclear weapons detonations.

Malnourishment is the most immediate impact of food insecurity. Humans can survive for a few weeks without food. A related impact is food poisoning as people turn to unsafe food options. This was an issue, for example, in a 1998 Quebec blackout, during which people ate food that had been in non-functional refrigerators for too long (EMP Comission 2008). As with water supply disruption, the search for food can pull people out of the labor pool. People are also less capable of work when they are hungry. The loss of labor can in turn lead to general malfunction of society. Food insecurity can also lead to infectious disease outbreaks, as has happened during several historical famines (Helfand 2013). Finally, these effects can also result in loss of law and order.

Module: Health Care Disruption

The provision of health care can be disrupted in several ways. Damage to infrastructure can result in hospitals and other facilities being destroyed or diminished by blast, electromagnetic pulse, fire, and potentially other effects. The disruption of transportation systems and telecommunications could reduce access to health care facilities and interfere with certain health care procedures. The effects of health care disruption are shown in Figure 17. The immediate impact is patient death. The general decline of health care infrastructure could also cause infectious disease outbreaks and an increase in other illnesses.

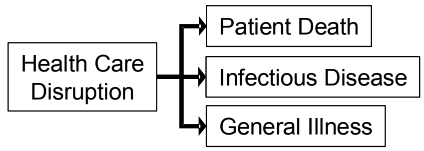

Figure 17. Effects of health care disruption caused by nuclear weapons detonations.

Module: Infectious Disease

Infectious disease outbreaks can be caused by food insecurity (Helfand 2013) and health care disruption. Infectious disease outbreaks can be major catastrophes in their own right. An important historical example is the 1918 flu, which broke out during WWI and ended up killing several times more people than the war. If a nuclear war leads to a new disease outbreak, that could be one of the largest effects of the war.

Figure 18 models two impacts of infectious disease: direct morbidity (i.e., illness) and mortality (i.e., death) from the disease and disruption to transportation systems. Transportation systems could be disrupted by the imposition of quarantines and other travel restrictions aimed at reducing the spread of the disease. There is thus a risk-risk tradeoff (Graham and Wiener 1995) between reducing the severity of the infectious disease outbreaks and avoiding the harms of transportation systems disruption.

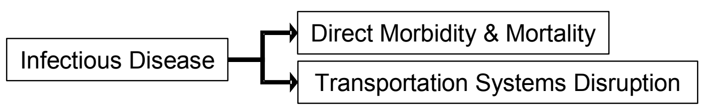

Figure 18. Effects of infectious disease caused by nuclear weapons detonations.

Infectious disease outbreaks are in their own right potentially complex catastrophes on par with nuclear war. Figure 18 captures only a small part of infectious disease impacts. For example, not shown in Figure 18 is the potential for infectious disease to result in food shortages (Huff et al. 2015). Future work should connect this paper's model to a more detailed model of infectious disease.

Module: Transportation Disruption

Transportation can be disrupted by blast, fire, and damage to infrastructure, with the effects shown in Figure 19. Blast from underwater detonations can capsize boats. Fire can send smoke into the atmosphere, disrupting aircraft (Frankel et al. 2013). Electromagnetic pulse can damage electronic infrastructure within road vehicles and airplanes, causing them to crash (EMP Commission 2008).

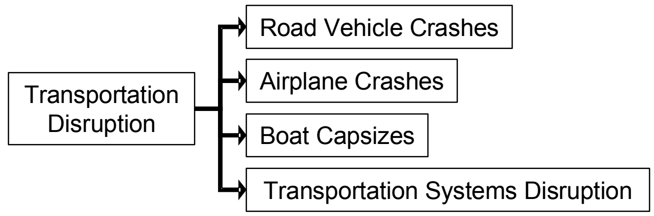

Figure 19. Effects of transportation disruption caused by nuclear weapons detonations.

Module: Transportation Systems Disruption

Transportation systems include vehicles as well as the infrastructure they depend on: roads, railways, energy supply, ports, labor, etc. Transportation systems can be disrupted by general disruptions to transportation and by disruptions to the energy supply. Transportation systems can also be disrupted by infectious disease outbreaks via quarantine and other travel restriction policies.

Transportation systems disruption can have a wide range of effects as shown in Figure 20. These effects all derive from a reduced ability to transport people, goods, and other things from place to place. Food insecurity comes from the breakdown of food supply chains. Water supply disruption comes from the inability to deliver emergency water. Health care disruption comes from failures of ambulances and other health care vehicles. Energy supply disruption comes from the breakdown of energy supply chains. Other supply chains can also break down. Enough supply chain breakdown could result in economic collapse and general malfunction of society. Loss of personal mobility, such as via the loss of fuel for automobiles in sprawling suburbs, can also result in the general malfunction of society. Reduced transportation can reduce the spread of infectious disease.

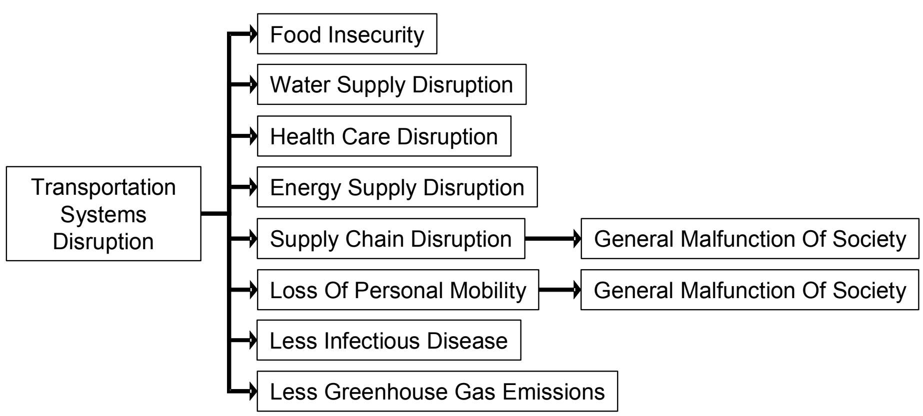

Figure 20. Effects of transportation systems disruption caused by nuclear weapons detonations.

Reduced transportation can also reduce greenhouse gas emissions. The effect could potentially be quite significant, especially for a large nuclear war. Sims et al. (2013) find the transport sector to cause about 16% of total greenhouse gas emissions.

Module: Energy Supply Disruption

Nuclear war can cause energy supply disruptions by damaging energy infrastructure or by disrupting the transportation systems used to transport energy. Figure 21 models the impacts of energy supply disruption. An immediate impact is the loss of heating and cooling, which can cause significant illness and death. The effect would be especially severe if the energy supply disruption occurs during a heat wave or winter storm. For comparison, an estimated 70,000 people were killed by the 2003 European heat wave (Robine et al. 2008). The death toll could have been even higher if Europe had a disrupted energy supply and could not use as much air conditioning. To be sure, a nuclear war can also block sunlight, which lowers temperatures. Taking that into account, winter storms could be the larger problem for energy supply disruption. One could rather morbidly hope that any nuclear war would occur during mild weather.

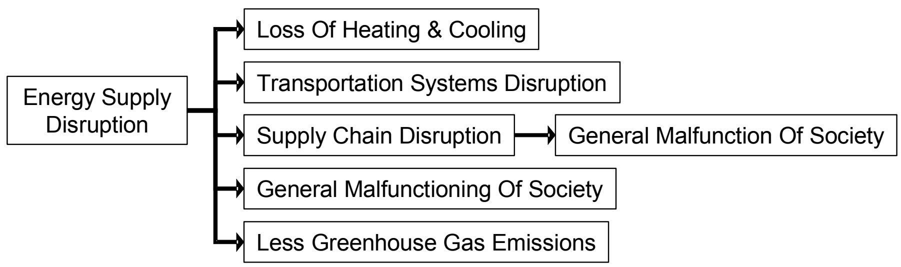

Figure 21. Effects of energy supply disruption caused by nuclear weapons detonations.

Energy supply disruption can have a range of other effects. It can disrupt transportation systems by depriving them of the energy needed to power vehicles. It can disrupt supply chains of all types, which in turn could cause general malfunction of society as basic goods stop being produced. It could cause general malfunction of society directly via the many ways that society uses energy. Finally, energy supply disruption could cause a reduction in greenhouse gas emissions, and potentially a very large reduction, due to the large role that the energy sector plays in greenhouse gas emissions. Bruckner et al. (2013) finds the energy sector to cause about 35% of total greenhouse gas emissions.

Impacts on greenhouse gas emissions could be long-lasting. OTA (1979, p.64-75) analyzes a nuclear war scenario in which the Soviet Union targets U.S. oil refineries. Its conclusions sound straight out of an environmentalist playbook: "Railroads and mass transit would supplant travel by cars and planes" (p.74). "Meat would become very much more costly in relation to other foods than it is now, and so would become a luxury" (p.75). Such changes could linger even after energy supplies are restored. However, despite the major risks that come from greenhouse gas emissions, none of this should be interpreted as justifying nuclear war.

Module: Satellite Disruption

There is one primary way in which nuclear war can disrupt satellites: by electromagnetic pulses that damage satellite electronics infrastructure. In July 1962, the U.S. conducted a high-altitude nuclear test detonation called Starfish Prime. The detonation damaged several satellites, including the AT&T telecommunications satellite Telstar 1, which then died despite only being a few months old (Frankel et al. 2013).

It is conceivable that nuclear war can disrupt satellites in other ways, such as by shooting nuclear missiles at adversary satellites. However, this is not an important possibility because non-nuclear anti-satellite technology is available and more desirable (e.g., because non-nuclear technology does not face the nuclear weapons stigma). States generally seek to avoid using nuclear weapons if the same mission can be achieved via other means.

Figure 22 shows two impacts of satellite disruption. One is telecommunications disruption, such as what occurred following the demise of Telstar 1. The other is astronaut death. EMP Commission (2008) analyzes the impact of a range of hypothetical high-altitude detonations on several satellites including the International Space Station. The analysis finds that a 5MT weapon detonated at a 200km altitude would give ISS astronauts “a 90 percent probability of death within 2 to 3 hours” (p.165). While such weapon yields are larger than those believed to exist in current nuclear arsenals, more common yields only increase the time to ISS failure from hours to days or weeks.

Figure 22. Effects of energy satellite disruption caused by nuclear weapons detonations.

Module: Telecommunications Disruption

Nuclear war can disrupt telecommunications by disrupting satellites and by a range of damage to telecommunications infrastructure. Two impacts of telecommunications disruption are modeled in Figure 23. One is impeded emergency services, due to the heavy reliance of emergency services on telecommunications. This in turn causes fire (or more precisely, prevents firefighters from putting out fires), health care disruption, and loss of law and order. The other is the general malfunction of society due to the many ways in which society depends on telecommunications: financial transactions, business email and conference calls, etc.

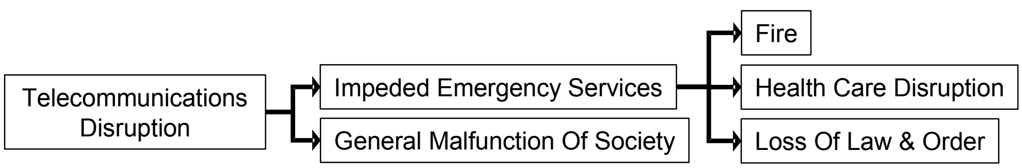

Figure 23. Effects of energy telecommunications disruption caused by nuclear weapons detonations.

Module: Shifted Norms

Nuclear weapons detonations and nuclear wars can influence some important societal norms. The influence comes from two sources: human perceptions of the detonation/war itself, and human perceptions of the ionizing radiation released by nuclear detonations. In practice, it can sometimes be hard to distinguish between the two. To a large extent, the two are intertwined: one cannot have a nuclear detonation without the release of ionizing radiation. However, one can discern distinct perceptions and norms. For example, ionizing radiation is not a significant factor for the high-altitude detonations that can cause damaging electromagnetic pulses. It is also not a significant factor for the very-high-altitude detonations that have been proposed for deflecting asteroids and comets (Remo 2015; Su 2015). Meanwhile, detonations are not a significant factor for ionizing radiation from other sources, such as nuclear power plants, for which strong human perceptions and norms exist. The ionizing radiation of nuclear weapons can likewise play a distinct role in shifting norms, including norms about nuclear power.

Figure 24 shows three norms that can be shifted by nuclear detonations, nuclear wars, and the ionizing radiation they release. The first is the norm against nuclear weapons. This norm is a major factor in nuclear arms control and the substantial general hesitance to use nuclear weapons in war. The norm may have been strengthened by Hiroshima and Nagasaki, with one observer calling the norm part of the "legacy of Hiroshima" (Schelling 2006). Indeed, following the Hiroshima and Nagasaki bombings, U.S. military officials sought to hide or downplay evidence of illnesses from ionizing radiation due to concerns that this would reduce public support for the U.S. nuclear weapons program (Tannenwald 2005), though the same fear has also been reportedly leveraged by the U.S. military to enhance nuclear deterrence (Jaworowski 2010).

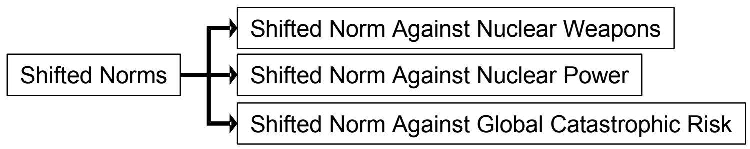

Figure 24. Effects of shifted norms caused by nuclear weapons detonations.

What would the norm against nuclear weapons be if nuclear weapons were not used in WWII? A wide range of answers are plausible. On one end of the spectrum, it is plausible that the norm would be even stronger, because there would be no precedent for nuclear weapons being used in war. A common (but contested) belief is that the nuclear bombings helped the U.S. win WWII while avoiding a costly land invasion (Wilson 2013). Had the U.S. refused to conduct the nuclear bombings, this could have sent a strong message that these weapons should not have been used under any circumstance.

On the other end of the spectrum, the norm could be weaker. The Hiroshima and Nagasaki bombings provided a vivid and enduring image of the horrors of nuclear war—hence the norm can reasonably be described as a legacy of the bombings. Without this image, there would be less to motivate the norm. A weaker norm could in turn have led to a nuclear war occurring later, especially during a near-miss event like the Cuban missile crisis. A later nuclear war would likely be much more severe, assuming some significant buildup of nuclear arsenals and especially if "overkill" targeting was used.

A new nuclear war could bring a similarly wide range of shifts in nuclear weapons norms. It could strengthen the norm, hastening nuclear disarmament. Already, there is a political initiative drawing attention to the humanitarian consequences of nuclear weapons use in order to promote a new treaty to ban nuclear weapons as a step towards complete nuclear disarmament (Borrie 2014). It is easy to imagine this initiative using any new nuclear attacks to advance their goals. Alternatively, it could weaken the norm, potentially leading to more and/or larger nuclear wars. This is a common concern, as seen for example in debates over low-yield bunker buster nuclear weapons (Nelson 2003). Given that the impacts of a large nuclear war could be extremely severe, a shift in nuclear weapons norms could easily be the single most consequential effect of a smaller nuclear war.

Norms about nuclear power can also be highly consequential. Fear of ionizing radiation from nuclear power inflates public concern about nuclear power relative to the actual medical risk (e.g., Slovic 2012). Some of this fear appears to derive from perceptions of nuclear weapons, especially Hiroshima and Nagasaki (e.g., Cwikel 1997). A new nuclear attack could strengthen general fears of nuclear radiation, further reducing support for nuclear power. Reduced support for nuclear power can in turn have major consequences to energy systems and the environment. Energy analysts are divided on the details, with some warning that increased use of fossil fuels could lead to more local air pollution and greenhouse gas emissions (Kharecha and Hansen 2013) and some instead seeing benefits from an increased use of renewable energy (Sovacool et al. 2013). Given the high stakes associated with energy systems, air pollution, global warming, and related issues, any shift in norms about nuclear power from nuclear war can have large impacts.

Finally, there could be general shifts in norms on global catastrophic risk. There is a general consensus that global catastrophic risk should be reduced. However, there is no consensus on how aggressively society should seek to reduce it. A large enough nuclear war could potentially be a global catastrophe. A smaller war could make people less interested in reducing global catastrophic risk by creating a perception that human civilization is invulnerable. Alternatively, it could increase interest by drawing attention to the fragility of human civilization.

Module: General Malfunction Of Society

Finally, food insecurity and the disruption of water supply, energy supply, transportation systems, and telecommunications could all cause society to malfunction. The intent of the general malfunction of society module is to broadly capture conditions in which the comforts and capabilities of modern society are not present. For example, one study found that nuclear war could result in economic malfunction so severe that currency may no longer be used, with transactions instead being conducted via barter (Cantor et al. 1989). General malfunction can also be defined as conditions in which society's resilience has been exceeded; at the global scale this could rate as a global catastrophe (Maher and Baum 2013; Baum and Handoh 2014).

Figure 25 shows potential effects of general malfunction of society. Two of the potential effects are loss of law and order and violent conflict. The idea here is that as people fall into desperate circumstances, they will tend to take desperate measures, including resorting to violence and committing other crimes. This idea has wide appeal but is highly contested in the scholarly literature. Studies of natural and human-caused disasters find that people do sometimes panic or misbehave, but they tend to act more cooperatively than they do under normal circumstances (e.g., Tierney et al. 2006; Rao et al. 2011). Studies of the effect of climate change and other environmental disturbances on violent conflict are inconclusive (e.g., Gleditsch 2012). This literature suggests that a general malfunction of society caused by nuclear could actually increase law and order and reduce violent conflict. However, nuclear war could create more dire circumstances than the events that have been studied in this literature, so historical precedents may not apply. The extent to which nuclear war could affect law and order or violent conflict, to our knowledge, has not been studied.

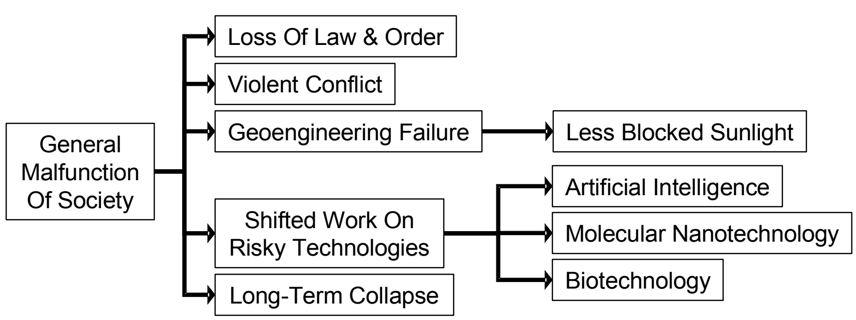

Figure 25. Effects of the general malfunction of society caused by nuclear weapons detonations.

One potential effect that has been studied is geoengineering failure. Geoengineering is the deliberate manipulation of Earth systems. Geoengineering is most commonly proposed as a way of lowering temperatures in response to global warming (e.g., Caldeira et al. 2013). One form of geoengineering involves injecting particles into the stratosphere in order to block incoming sunlight. This is a controlled version of the blocked sunlight shown in the fire module of this paper. The particles fall out of the atmosphere after a few years and would have to be continually replaced. A general malfunction of society could eliminate the capacity to replace the particles, at which point temperatures would rapidly rise to where they would have been without the geoengineering (Matthews and Caldeira 2007). The rapid temperature increase could itself be a global catastrophe, which would follow the nuclear war in what has been called a "double catastrophe" (Baum et al. 2013).

Another link between nuclear war and other major catastrophes comes from the potential for general malfunction of society shifting work on risky technologies such as artificial intelligence, molecular nanotechnology, and biotechnology. The simplest effect would be for the general malfunction of society to halt work on these technologies. In most cases, this would reduce the risk of harm caused by those technologies. It is also conceivable that in the absence of a functional society, safety measures would decay, resulting in the release of harmful technologies (or substances developed via the technologies). For example, stores of dangerous pathogens could escape their laboratories. However, this is a speculative possibility and may be unlikely or impossible, depending on the details of how the technologies/substances are stored.

Alternatively, the general malfunction of society could increase risk from risky technologies by creating an incentive to taking risks. The incentive would be especially strong for technologies like artificial intelligence and molecular nanotechnology that could conceivably help society recover from the nuclear war. This creates a "great downside dilemma" on whether to launch the technology in hopes of recovering from nuclear war but with the possibility of the technology itself causing a major catastrophe (Baum 2014).

Finally, the general malfunction of society could cause a long-term collapse of human society. Such a collapse has been feared in the context of a variety of risks (e.g., Diamond 2005; Randers 2008; Butzer and Endfield 2012). A long-term collapse could be an extremely harmful impact, arguably on par with human extinction (Bostrom 2002; Maher and Baum 2013). The extent to which general malfunction of society as caused by nuclear war could result in long-term collapse is an important question, one that should be a priority for future research.

Conclusions

Nuclear war can have a wide range of impacts. The nature of the impacts depends on the specifics of the nuclear war scenario, including the number of weapons detonated, the design of the weapons detonated, and the locations where they are detonated. The impacts can include major disruptions to ecosystems and human society. The most severe effects generally occur near the detonations, but significant effects can occur worldwide.

This paper presents a model for the impacts of nuclear war. The model includes many different types of impacts that can follow from each of the immediate effects of nuclear war: thermal radiation, blast, ionizing radiation, electromagnetic pulse, and human perceptions. To our knowledge, this is the first attempt at modeling the full range of major impacts of nuclear war. The model includes original detail on systemic effects, including interactions between nuclear war and other major catastrophes.

In reflection upon this paper's model, it is notable just how many ways that nuclear war can cause harm. Much of the damage can come from secondary effects on infrastructure systems and the global environment instead of the primary local explosion. This complicates military strategy. In a war, nuclear detonations would mainly be used for defeating the adversary's military ("counterforce" targeting) or destroying its population ("countervalue" targeting). The secondary effects could further destroy the adversary population, but with some major downsides.

One downside is that much of the damage is long-lasting and could persist long after the end of the war. For comparison, landmines have been stigmatized and banned in large part because they continue to cause harm long after they have been placed. The fact that nuclear weapons can do so too puts them in precarious moral and legal standing. On the other hand, all weapons can have long-lasting effects. Indeed, many of the effects modeled in this paper, including much of the damage to infrastructure, can be achieved to varying degrees using conventional weapons.

Another downside is that the damage can spread far beyond the targeted location. Some of the effects would be felt everywhere in the world, including in the state that carries out the nuclear attack. Robock and Toon (2012) call this "self-assured destruction". Robock and Toon refer specifically to the global environmental effects, but the same logic also applies for other effects such as supply chain disruption or the spread of infectious disease.

The potential for nuclear war to cause infectious disease outbreaks speaks to another theme of this paper's model: the numerous interactions between the impacts of nuclear war and other catastrophic risks. Nuclear war can lead to infectious disease outbreaks. It can affect global warming by changing greenhouse gas emissions. It can cause the failure of stratospheric geoengineering. And it can affect the development and use of risky new technologies. Each of these other catastrophes could potentially be as large as even a large nuclear war. How nuclear war affects these other risks could be among the most significant impacts of nuclear war.

Another major effect is how one nuclear war impacts the potential for additional nuclear wars. This can occur in particular via shifting the norm against nuclear weapons. A nuclear war could either strengthen or weaken this norm, depending on the details of the war and how it is perceived by the international community. This effect could be one of the largest impacts of nuclear war, especially for smaller nuclear wars.

A Research And Policy Agenda

The impacts of nuclear war are important to a number of major policy questions, as discussed in the "Why This Is Important" section of the Introduction. Answering the policy questions benefits from a detailed understanding of the nature of nuclear war impacts as well as quantitative estimates of the total severity of the impacts for a range of nuclear war scenarios. A nuclear war research agenda should focus on those aspects of the impacts that are most important for policy decisions.

With that in mind, here are some steps for future research that would make progress towards understanding and quantifying the impacts of nuclear war:

- Factor in the conventional military activities that can accompany a nuclear war. As seen in WWII, the conventional military activities can be even more significant than the nuclear attacks.

- Refine the study of the systemic effects on infrastructure and the accompanying human consequences. While there have been some good prior studies of this, most notably EMP Commission (2008), these are in limited supply relative to studies of the local physical effects and global environmental effects.
- Study the global effects of regional infrastructure destruction, as in the nascent field of global systemic risk (Centeno et al. 2015).
- Connect this paper's models to models of other catastrophic risks, such as epidemiological models relating infrastructure, food security, and infectious disease (Huff et al. 2015).
- Analyze and model the ways in which nuclear war could result in the long-term collapse of human civilization and/or human extinction.
- Develop mathematical relations for all parts of the model and implement them in computer code so as to enable calculation of the severity of different aspects of nuclear war for different nuclear war scenarios.
- Link this impacts model with models of the probability of nuclear war and of nuclear war scenarios in order to characterize and quantify the total risk of nuclear war.

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