# Winter-Safe Deterrence: The Risk of Nuclear Winter and Its Challenge to Deterrence

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**Abstract**
A new line of nuclear winter research shows that even small, regional nuclear wars could have catastrophic global consequences. However, major disarmament to avoid nuclear winter goes against the reasons nuclear weapon states have for keeping their weapons in the first place, in particular deterrence. To reconcile these conflicting aims, this paper develops the concept of winter-safe deterrence, defined as military force capable of meeting the deterrence goals of today's nuclear weapon states without risking catastrophic nuclear winter. The article analyzes nuclear winter risk, finding a winter-safe limit of about 50 nuclear weapons total worldwide. The article then evaluates a variety of candidate weapons for winter-safe deterrence. Non-contagious biological weapons (such as anthrax or ricin), neutron bombs detonated at altitude, and nuclear electromagnetic weapons show the most promise. Each weapon has downsides, and the paper's analysis is only tentative, but winter-safe deterrence does appear both feasible and desirable given the urgency of nuclear winter risk.

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Nuclear winter is back. Prominent in the 1980s, the topic faded from view following the end of the Cold War, only to re-emerge in recent years with a new, more advanced scientific study. The new results are in some ways more grim than the results of the original 1980s research, with catastrophic global consequences shown to follow from a war with as few as 100 nuclear weapons, or possibly even fewer. Meanwhile, global arsenals hold 16,000 total nuclear weapons and are not projected to go below 100 nuclear weapons any time soon. Despite calls for rapid disarmament and attempts to shift nuclear doctrine, nuclear weapons remain central to the security policies of nuclear weapon states, especially for deterrence.

This paper evaluates prospects for *winter-safe deterrence*, defined here as a military force capable of meeting the deterrence goals of today's nuclear weapon states without risking catastrophic nuclear winter. If feasible, this would be a win-win situation: Nuclear weapon states win because they continue to achieve their security goals, and all countries—including nuclear weapon states—win because they are no longer threatened by nuclear winter. Nuclear weapon states should pursue winter-safe deterrence both because it helps (or at least does not significantly hurt) their national security and because it is morally the right thing to do. This is ethics with strategy: By pursuing policies that nuclear weapons states find desirable, the policies are more likely to be implemented.

Nuclear winter only occurs when a sufficiently large number of nuclear weapons are used, so winter-safe deterrence does not require a world without nuclear weapons. There is considerable uncertainty surrounding both the form of future wars and the human impacts of nuclear winter. Therefore, the paper conducts risk analysis to identify a winter-safe nuclear arsenal size given the current state of knowledge. A limit of 50 total nuclear weapons worldwide is proposed. With only 50 total nuclear weapons, a severe nuclear winter catastrophe is very unlikely to occur, though some harmful nuclear winter effects could still occur. The 50 weapon limit potentially could be increased pending results of future research aimed at reducing the uncertainty surrounding the human impacts of nuclear winter.

50 total nuclear weapons worldwide is not zero, but it would require radical reductions in the arsenals of all current nuclear weapon states except North Korea. Nuclear weapon states claim that the security conditions conducive to further disarmament do not yet exist and can only be realized through a gradual, step-by-step process. Meanwhile, the entire world—including nuclear weapon states—is at risk. The paper therefore asks if there is another way that these states can achieve their deterrence goals without risking nuclear winter or any other comparably severe global catastrophe.

This search for winter-safe deterrence is conducted by scanning the landscape of candidate weapons and evaluating each according to its capacity to deter. The weapons considered are small nuclear arsenals (within the 50 worldwide limit), conventional military force, neutron bombs, conventional prompt global strike, biological and chemical weapons, cyber weapons, and electromagnetic weapons. None of these weapons offers the same destructive potential as a large nuclear arsenal, some of these weapons are simply ineffective deterrents, and one of them (contagious biological weapons such as weaponized smallpox or Ebola) risks global catastrophe comparable to nuclear winter. However, some of the weapons could work. Non-contagious biological weapons (such as anthrax or ricin) or neutron bombs detonated at altitude show the most promise for holding large populations at risk. Nuclear electromagnetic weapons (regular nuclear weapons detonated at high altitude) show the most promise for holding built infrastructure at risk. These results are tentative, in particular because they derive from technical analysis with limited attention to political acceptability. However, from this initial analysis, winter-safe deterrence does appear feasible and—given the severity of nuclear winter risk—desirable.

This paper contributes jointly to literatures on nuclear winter and deterrence. While the environmental science of nuclear winter is increasingly robust, its policy implications have received less attention since the 1980s.[1] Nuclear winter risk has also received limited prior attention, but it is crucial for estimating winter-safe arsenals. Winter-safe deterrence is not the only possible policy response to nuclear winter risk, but it is an important one. Other policy responses include abandoning deterrence, which is a bitter pill for nuclear weapon states to swallow; preparing to survive nuclear winter, which is a dreary if plausibly feasible project;[2] or doing nothing and gambling that no nuclear winter occurs. In light of these alternatives, winter-safe deterrence merits consideration. To the deterrence literature, this paper contributes original analysis of mixed deterrence (i.e., deterrence involving a mix of weapon types) under the novel constraint of no nuclear winter or other global catastrophe. As military technology evolves, the deterrence potential of new and old weapons alike is constantly being reevaluated. This paper evaluates a sizable list of familiar and unfamiliar weapons options, reaching new conclusions on the new concept of winter-safe deterrence.

## The Science of Nuclear Winter

The concept of nuclear winter was first developed in the early 1980s by scientists including Paul Crutzen, who later won a Nobel Prize in Chemistry for his work on the ozone hole, and legendary astronomer Carl Sagan.[3] Sagan went to great lengths to raise awareness about nuclear winter in the 1980s and early 1990s.[4] This episode apparently had some influence on policy, with Mikhail Gorbachev citing it as a factor in his desire to cool that era's nuclear tensions and reverse the arms race.[5] After fading from the spotlight, nuclear winter began a bit of a comeback in 2007 with the publication of new research examining nuclear winter with the latest scientific models.[6] Several follow-up studies and commentaries have been published since, and research is ongoing.[7]

In technical terms, 'nuclear winter' refers specifically to a cooling of Earth's surface such that winter-like temperatures occur during summer, as caused by a sufficiently large nuclear war. Cooling to warmer-than-winter temperatures can be called 'nuclear autumn'. Per this definition, nuclear winter/autumn is part of a broader suite of environmental consequences of nuclear war. However, all of the environmental consequences can have profound consequences for the planet and for human civilization, and likewise are important for policy. No separate term has been coined for the full suite of environmental consequences of nuclear war, so this paper will use 'nuclear winter' as shorthand for the full suite. This use of 'nuclear winter' may be interpreted metaphorically: a time of cold, darkness, and death.

Nuclear winter is caused by the burning of cities, industrial facilities, trees, and other flammable materials, which sends smoke into the atmosphere. The main effects of the smoke derive from the fact that the smoke rises high up into the atmosphere, past the clouds, into the stratosphere where it will not quickly fall back out in rain. At this altitude, the smoke spreads across the planet and gradually falls back out over the next ten to twenty years. While it is aloft, the smoke absorbs incoming sunlight and blocks it from reaching the surface. As the smoke absorbs sunlight, the stratosphere warms, causing ozone depletion at a potentially massive scale.[8] The ozone depletion causes more ultraviolet radiation to reach Earth's surface. Increased UV radiation can harm living organisms, including humans. Harmful effects include skin cancer and eye damage to animals and the inhibition of photosynthesis in plants.[9] Meanwhile, the smoke blocking sunlight from reaching the surface causes colder surface temperatures and less precipitation. Precipitation declines because there is less heat to power the hydrological cycle. The main harmful effect that has been identified is a decline in plant growth, including agricultural production. Secondary effects could include disease outbreaks and additional conflicts.[10] The effects occur worldwide, regardless of where the detonations occur, though detonation location can affect the spatial distribution of impacts.

For both UV radiation and cooling, the magnitude of the disruption is proportionate to the amount of smoke put into the atmosphere, which in turn depends on the number of nuclear detonations, the bombs' yields, the detonation locations, and other factors. Regarding detonation location, a key variable is whether the detonation occurs in a city, and if it does, the population density of the city. Other locations such as industrial zones can also produce significant quantities of smoke. This is why nuclear weapons testing has not caused nuclear winter: The tests were conducted in remote locations or at high altitude, and thus did not have much to burn.

The location of a city on the globe can also make a difference given Earth's topography and atmospheric circulation patterns, but this effect is smaller.

The most heavily studied nuclear winter scenario involves war between India and Pakistan in which each country uses 50 nuclear weapons, each with a 15 kiloton yield, comparable to the Little Boy weapon dropped on Hiroshima. The studies assume that the weapons are dropped on each country's major cities, and not on e.g. remote military targets, producing 5 teragrams of smoke.[11] In this scenario, ozone loss would range from 20% to 70% from low to high latitudes.[12] Temperatures would fall about 1.25ºC within the first year. Even ten years after, temperatures would still be about 0.5ºC below normal.[13] Crop yields in China and the Midwestern United States are projected to decline by around 10-30%.[14] One analysis estimates that at least two *billion* people would be at risk of starvation.[15] A core point is that even a 'limited' regional nuclear war could have catastrophic global consequences. It should be emphasized that what drives nuclear winter is the quantity of smoke entering the stratosphere, not where the nuclear war occurs. Thus a comparably large nuclear war between other countries would have similar global climatic and humanitarian effects. The India-Pakistan scenario offers an illustrative and relatively probable case, but any nuclear weapon state except North Korea could produce similar effects.

A larger nuclear exchange involving American and Russian arsenals would cause further disruption. An exchange of about 1200 weapons could produce about 50 teragrams of smoke, causing temperatures to fall by about 4ºC. For 4000 weapons—around what New START prescribes—there could be 150 teragrams of smoke, with a temperature fall of about 8ºC. Agriculture failure would be so severe and widespread that it becomes easier to count the survivors than the fatalities.[16] Climate scientist Alan Robock, who has led many of the recent nuclear winter studies, expects some survivors 'especially in Australia and New Zealand'.[17] While this is hardly a cheerful evaluation, even this may be too optimistic. Hopefully some people somewhere would find some way to survive. But the conditions would be harsh enough that survival is no guarantee.[18]

Finally, it should be acknowledged that, over the years, there has been some scepticism of whether nuclear winter would actually occur, or would occur with enough severity to be worth factoring into security policy.[19] To an extent, one cannot be sure what would happen, because a large exchange of nuclear weapons has fortunately never occurred. However, there are at least two reasons to believe that the current round of nuclear winter science is yielding results that are at least in the general vicinity of what would actually happen. One reason is that the science uses modern climate models developed for the study of global warming. Global warming has its own sceptics and controversies, which has led to the climate models being heavily scrutinized.[20] Climate science may well be the most carefully vetted of all the sciences. The nuclear winter researchers are themselves distinguished climate scientists and are using state-of-the-art climate models. And two distinct nuclear winter research groups from two different countries using two different sets of models both report approximately the same results.[21] While some uncertainties in the science of nuclear winter remain and additional research could provide additional confidence, it should be expected that the current research results are basically sound.

The second reason for believing that nuclear winter would occur is that it has a historical precedent in volcano eruptions. Volcano eruptions, like nuclear weapon detonations, cause large amounts of smoke to rise into the atmosphere. An insightful example is the 1815 Mount Tambora eruption. The Tambora eruption caused temperatures to fall by about 0.5ºC, resulting in major food shortages and other disruptions, such that 1816 is now known as the 'Year Without

Summer'.[22] While humanity ultimately survived Tambora, nuclear war could put even more smoke into the atmosphere and cause more severe disruption. It thus is important to factor into nuclear security policy.

**Risk Analysis of Winter-Safe Nuclear Arsenal Limits**

It is in every country's interest to avoid nuclear winter. No country would benefit from the increased exposure to UV radiation and decreased agricultural yields, among other harms, all of which would occur worldwide regardless of where the weapons were used. This point raises two questions: what is needed to avoid nuclear winter, and how far countries should go to avoid it. Answering both questions suggests adhering to limits to nuclear weapon arsenal sizes that keep the world safe from nuclear winter. Given uncertainty about both what future wars may occur and the severity of nuclear winter if nuclear war does occur, answering these questions benefits from analysis to identify policies that perform well in light of the uncertainty.

The severity of nuclear winter is a function of the amount of smoke produced in a nuclear exchange, which in turn depends on the number, yield, and location of detonations in the exchange. How small of a nuclear arsenal would be needed to keep human civilization safe from nuclear winter? The short answer is, nobody knows. Modern climate modelling provides a pretty good understanding of the climatic consequences. There are some important uncertainties in the climate science, but the big uncertainty is how well humans will cope. Research on the all-important human factor is frighteningly scarce, limited mainly to a few studies connecting the climate science to agricultural models.[23] This research is instructive, but it leaves basic questions unanswered about the total human impacts of nuclear winter.

Consider one of the most detailed studies of the human consequences of nuclear winter, by Ira Helfand of the International Physicians for the Prevention of Nuclear War.[24] This is the study that found at least two billion at risk of starvation from an India-Pakistan exchange of 100 nuclear weapons (50 per country). The two billion estimate comes from converting agriculture declines into nutrition loss for the people who are already malnourished. As the study notes, the figure does not estimate deaths from second-order effects like disease outbreaks and additional conflicts. Perhaps a mild nuclear winter could even trigger a conflict in which additional nuclear weapons are built and used. The stakes may be even higher in the future as developments in synthetic biology, geoengineering, and other technologies render civilization more powerful but less stable.[25] The bottom line is that even a smaller nuclear exchange might have catastrophic global consequences. But on the other hand, it might not. Nobody knows.

Making policy under such heavy uncertainty is a difficult challenge, but it is also a familiar one. One cannot predict the consequences of a military campaign, but decisions on whether and how to wage it must be made. One cannot predict the consequences of a new technology, but decisions about whether and how to regulate it must be made. And so on for quite a large portion of ongoing policy decisions.

Here it is important to bring in the ethics of global catastrophic risk. A global catastrophe is an event that causes great harm to the entirety of global human civilization. Catastrophes of this magnitude take on a special ethical significance. Carl Sagan was perhaps the first to recognize this in his own discussion of nuclear winter. The astronomer saw the big picture: Human extinction means the loss of all people who could ever exist into the distant future.[26] Contemporary scholars further understand that even without total human extinction, a permanent collapse of human civilization is of comparable significance.[27] Ultimately what is at stake is the long-term trajectory of human civilization, its success or its failure.

Ethical obligations to future generations are fundamentally different from those to people alive today, for two reasons. First, future generations vastly outnumber the current population. Barring catastrophe, humanity could survive for millions or even billions of years into the future. Thus anything that affects the long-term trajectory of human civilization is of much greater consequence than things that only affect people today.[28] Second, despite their great number, future generations are utterly helpless. They cannot vote in today's elections or trade in today's markets, and they certainly cannot deter today's countries with any weapons. This is absolutely unfair, but that is just how it is.[29] The only reason people must help future generations is because it is the right thing to do.

For nuclear winter policy, the basic point is that when a permanent global catastrophe could occur, a cautious approach is generally warranted.[30] This means erring on the side of smaller nuclear arsenals. Any given nuclear weapons exchange has a range of possible outcomes of varying severities and probabilities. A permanent global catastrophe is so severe of an outcome that even a small probability of it happening is a large risk and thus worth avoiding. A winter-safe arsenal would thus be one that has a sufficiently small (perhaps zero) probability of causing a permanent global catastrophe.[31]

It should be noted that the uncertainty surrounding nuclear winter can be reduced through further research. A cautious approach in which uncertainty gradually shrinks suggests a small initial arsenal that could gradually increase as research eliminates the possibility of certain worst-case scenarios. In other words, the world maintains low limits on nuclear arsenals until it learns that higher limits are winter-safe—and higher limits might end up not being winter-safe, depending on what the further research finds. Of course, such an approach is opposite to the current state of affairs, which features large arsenals that are gradually being reduced. Per the logic here, the people who built these arsenals were not being appropriately cautious. The fact that they did not even know about nuclear winter only underscores this: What other perils have not yet been identified?

With this in mind, at this time a reasonable security policy would permit no more than about 50 Hiroshima-sized nuclear weapons total, shared across all countries. This is smaller than even the arsenals in the hypothetical India-Pakistan studies discussed above, and smaller than the arsenal limits proposed in prior nuclear winter policy studies.[32] Those studies did not point directly towards a permanent collapse of global human civilization, but many dangerous indirect effects have not yet been accounted for. Given how high the stakes are, it is important to err on the side of caution with weapon limits low enough that provide confidence that the world is safe from nuclear winter. Given the present state of knowledge, 50 weapons is a reasonable winter-safe limit. Further research could reduce the uncertainty, potentially bringing a higher limit.

The 50 weapon limit does not strictly guarantee that no catastrophic nuclear winter occurs. If nothing else, a 50 nuclear weapon war plausibly could trigger a new arms race and larger nuclear war, resulting in a nuclear winter catastrophe. But the 50 weapon limit does make the probability of catastrophic nuclear winter very small. By limiting arsenals to 50 total weapons *worldwide*, there is additional safety because most potential nuclear wars do not involve the entire global arsenal. Of course, catastrophic nuclear winter might still not occur under larger arsenal sizes. Indeed, nuclear war might never occur, and if it does, it might involve more limited weapons exchanges. But there is no guarantee of this; indeed there is a nontrivial probability of large-scale nuclear war as discussed above. A 50 weapon limit leaves only a minimal risk of catastrophic nuclear winter. It is a policy that performs well given the uncertainty about both what wars might occur and how severe nuclear winter would end up being.

**The Need For Winter-Safe Deterrence**

A global limit of 50 nuclear weapons is in sharp conflict with the policies of today's nuclear weapon states. All of them except North Korea have more than 50; most have multiple times this number.[33] While most of them are reducing the size of their arsenals, the process is slow, and meanwhile there is a risk of nuclear winter. The continued possession of nuclear weapons presumably brings some benefits for the nuclear weapon states, but these benefits are vastly smaller than the harm of permanent global catastrophe that destroys the long-term viability of human civilization. Following this logic, nuclear weapon states should take great effort to bring their arsenals down to winter-safe levels.

It is easy to point fingers at nuclear weapon states for not disarming faster. Indeed, many do. To pick one of many examples, at the 2014 Nuclear Non-Proliferation Treaty (NPT) Preparatory Committee meeting, Brazil remarks that "If there is a crisis in the NPT, it is mainly due to the failure to disarm, rather than due to actual proliferation." [34] It is likewise understandable that Brazil, other non-nuclear weapon states, and disarmament activists would be disappointed that the nuclear weapon states have not yet completely disarmed. The risk of nuclear winter provides even more reason to be disappointed, and also to be afraid, because nuclear winter means that non-nuclear weapon states can be gravely harmed by nuclear weapons even if they are not targeted.

At the same time, it is important to recognize that the nuclear weapon states have reasons for their continued possession of nuclear weapons. While there can be many reasons for having nuclear weapons, perhaps the most important is deterrence. Despite the end of the Cold War and the shift of attention towards terrorism and rogue states, deterrence remains central to nuclear weapons states' security policies.[35] Nuclear deterrence features prominently in the 2010 USA Nuclear Posture Review,[36] the 2013 French White Paper on Defence and National Security,[37] the 2010 UK Strategic Defence and Security Review,[38] China's 2012-2013 White Paper on The Diversified Employment of China's Armed Forces,[39] and the 2010 Military Doctrine of the Russian Federation,[40] among many other documents, statements, and discussions of these countries' security policies. Asking nuclear weapon states to rapidly and completely disarm is asking them to give up their nuclear deterrence doctrines, which they are reluctant to do.

To be sure, there are arguments against the doctrine of nuclear deterrence. One argument is moral, claiming that nuclear weapons are fundamentally inhumane and should be banned regardless of their role in deterrence.[41] Another argument is empirical, claiming that nuclear weapons are not as effective as deterrents as they are widely believed to be.[42] These are important arguments worth taking seriously. And perhaps these arguments will succeed. But meanwhile, the security goals of nuclear weapon states must be acknowledged. Reducing nuclear winter risk is an important ethical objective, but sound strategy towards meeting this objective should factor in the needs of the states whose weapons create the risk in the first place. A win-win policy that both reduces the risk and helps nuclear weapon states is more likely to be implemented and thus more likely to reduce the risk.

Another important point is that, as long as deterrence succeeds in avoiding conflict, nuclear winter is irrelevant, and large nuclear arsenals can be kept. The problem is that deterrence could fail. Indeed, deterrence becomes likely to fail over long periods of time.[43] A careful reading of history suggests that nuclear deterrence has already failed or almost failed several times. For example, the Soviet nuclear arsenal did not deter Kennedy's escalation during the Cuban missile crisis.[44] Even since the end of the Cold War, false alarms have threatened to inadvertently trigger nuclear war, such as the 1995 Norwegian rocket incident, suggesting an ongoing risk of inadvertent nuclear war.[45] It is unreasonable to assume nuclear deterrence will never fail. Furthermore, even if the probability of nuclear war is low, the consequences are so severe that it constitutes a large risk.

At some point, nuclear deterrence could become unnecessary if nuclear weapon states cease to consider each other adversaries at a level requiring nuclear deterrence.[46] Indeed, non-adversarial relations may be in the process of happening.[47] But it is a slow process. Meanwhile, each successive year that nuclear weapons still exist is a year in which they could be used. Tensions can flare up at any time; the ongoing (at the time of this writing) Ukraine crisis is a worthy reminder of this. The possibility of inadvertent nuclear war from random false alarms suggests that nuclear war might even be possible during periods of low tensions. Faster solutions than achieving non-adversarial relations are worth pursuing.

Aside from abandoning the doctrine of deterrence and achieving non-adversarial international relations, there are at least two additional options for reducing nuclear winter risk. One option is to make preparations for surviving nuclear winter. This could include stockpiles of food and other necessities, or some means of producing them during the years of nuclear winter.[48] It could also include shielding against UV radiation. Additional preparations regarding security and governance institutions, telecommunications, or other sectors may further be necessary and/or desirable. If such preparations are made, then nuclear winter might not be an especially severe global catastrophe. Such preparations would be additionally desirable by making human civilization more resilient to a variety of other local and global catastrophes.[49] Perhaps nuclear weapon states could sponsor such preparations in exchange for keeping their nuclear weapons.[50] At a minimum, nuclear weapon states would want such preparations for their own countries to keep their citizens alive, just as they would seek to provide gas masks, bomb shelters, and other civil defence measures. This may be enough to avoid a permanent collapse of global civilization, though it would still put civilization and its members in an uncomfortable position (to say the least) for a period on the order of 10 years.

The other option is deterrence with winter-safe weapons. Such weapons would achieve deterrence goals without threatening catastrophic nuclear winter, or any other global catastrophe. Given the enduring role of deterrence in security policy, the difficulty of quickly achieving non-adversarial international relations, the possibility that deterrence could fail, and the discomforts of surviving nuclear winter, winter-safe deterrence is worth consideration. While some people have claimed that nuclear weapons are the only viable deterrents,[51] there has been little systematic evaluation of the available options.

**The Search For Winter-Safe Deterrence**

Winter-safe deterrence is military force that can (1) offer adequate deterrence, as judged by today's nuclear weapon states, while (2) keeping the world safe from nuclear winter or other global catastrophes. Before diving into the details of specific weapons, it is worth considering important attributes of a deterrent. The essence of a deterrent is to dissuade other actors from taking certain actions: 'If you do X, then I will do Y'. The deterrent must be perceived as threatening something that the other side values, such as military forces, political leadership, civil infrastructure, and the health and lives of civilians. The threat (Y) must be perceived as so bad that it outweighs the benefits of the initial action (X). Deterrence is ultimately psychological, and so actually threatening something is not strictly necessary, as long as there is the perception of threat. However, the forthcoming analysis focuses on what the various weapons actually threaten, under the assumption that the perceived threat is similar. Additional psychology is discussed when it is known, such as in the fears induced by certain types of weapons.

A few other technical attributes of deterrents are crucial. The deterrent must be visible: The other side cannot be deterred by what it is unaware of. This means that whoever wants to deter must announce their deterrent. Likewise, there must not be significant defensive measures that the other side can take, even after the deterrent has been announced. Otherwise the threat would be weakened. Additionally, the deterrent must be able to survive a first strike so that it can be used for a retaliatory second strike. Otherwise, the weapon could be removed in a first strike, which is a deterrence failure. Announcing the existence of the deterrent cannot cause it to become vulnerable to first strike. Finally, in light of the nuclear winter discussion, the deterrent must only cause localized effects, or at most mild global effects; it must not threaten global catastrophe.

There are also some important political conditions that new deterrents should meet. New deterrents ideally would not pose significant proliferation risk, shift geopolitical power in terms unfavourable to nuclear weapon states (otherwise these states would not want to disarm their nuclear weapons), or destabilize the international system (which could introduce sizable risks on its own). Arguably, human civilization is safer with some worsening of these conditions if it eliminates nuclear winter risk. However, ideally such a trade-off would be avoided. Furthermore, if these conditions are not met, then nuclear weapon states may not want to disarm their nuclear arsenals. For example, Israel, North Korea, Pakistan and Russia all lean heavily on nuclear deterrence for their security. These states are unlikely to abandon their nuclear arsenals in favour of any new deterrent regime that would leave them insecure. Political acceptability is thus necessary for the success of any winter-safe deterrent. Importantly, political acceptability may not be such a daunting hurdle to clear if states recognize the threat that nuclear winter poses to themselves. In other words, winter-safe deterrence does not need to be politically attractive *per se*—it only needs to be more attractive than deterrence with large nuclear arsenals.

With that in mind, here is an overview and initial analysis of several possibilities for winter-safe deterrence. Each of the weapons analyzed has certain advantages and disadvantages, making them suitable for certain deterrence situations. The analysis here is not intended to be either comprehensive or conclusive, but instead aims to provide a first-order assessment of the possibility of winter-safe deterrence. The analysis focuses mainly on technical issues, not political acceptability. Both are important, but more can readily be said on the technical issues, making them a better starting point.

### *Small Nuclear Arsenals*

A world without nuclear weapons is a desirable goal, but it is not needed to avoid nuclear winter. A winter-safe deterrence regime can still have some nuclear weapons. A global limit of 50 nuclear weapons still permits five to ten nuclear weapons across five to ten countries. This is not much, but it could be enough to contribute significantly to a deterrence regime. After all, even a single nuclear weapon could cause catastrophic harm, albeit not on the global scale. The power of a single nuclear weapon is apparent from the great efforts the international community now makes to prevent nuclear proliferation to rogue states and nonstate actors.[52] Small nuclear arsenals would need to be heavily shielded so that they cannot be taken out by a first-strike attack. Assuming this is possible, small nuclear arsenals could contribute to a winter-safe deterrence regime.

Research and debate on minimum deterrence and related concepts have long considered the deterrence capacity of small nuclear arsenals.[53] One basic conclusion is that there is no single number of nuclear weapons that guarantees an effective deterrent. The minimum number of weapons needed depends on the ability of weapons systems (including delivery vehicles and command and control systems) to survive first-strike attacks, the number and size of adversaries to be deterred, the capabilities of adversary missile defences, and adversaries' psychological propensities to be deterred, among other factors. That said, the number of weapons does make for a convenient approximate metric. Estimates for the minimum number of nuclear weapons needed for deterrence vary widely, from as low as ten survivable weapons[54] to as high as 1,700.[55] The most common estimates fall in the range of about 100 to 500, with 311 being one notable estimate.[56] This middle range corresponds with the arsenal sizes of China and India, which both follow minimum deterrence doctrines. 100 weapons per nuclear weapon state is not even close to being winter-safe per this paper's standard, though it would be winter-safe per some previous standards.[57] Ten weapons per nuclear weapon state is close but still too large. Ten *survivable* weapons could mean more than ten total weapons. And those weapons would have countervalue targeting, which typically means aiming at cities. Cities produce more smoke than other targets, causing more nuclear winter. Thus even the most optimistic estimates of minimum nuclear deterrence still leave arsenals that risk catastrophic nuclear winter.

Aiming nuclear weapons at cities raises additional issues. Doing so threatens civilians and thus may violate the Law of Armed Conflict. For this reason the United States Nuclear Employment Strategy states that it 'will not intentionally target civilian populations or civilian objects'.[58] Such humanitarian concerns are important. However, the humanitarian consequences of nuclear winter are vastly larger than those of targeting cities. A humanitarian case can be made for targeting cities if it reduces nuclear winter risk. But such a controversial matter merits further debate.

A common concern about small nuclear arsenals is that they are more vulnerable to preemptive attack and thus less stable. Even a minimum nuclear deterrent would, by definition, deter. But a minimum deterrent may be too large for winter-safety. Smaller-than-minimum nuclear arsenals would risk preemption if they are not augmented by additional weapons in a multiple-weapon deterrent system. Preemption risk could be especially large if the nuclear arsenals are subject to international verification for compliance with winter-safety protocols. The deployment of missile defence systems could further increase preemption risk by limiting second-strike capability. Thus it is important to consider what additional weapons could enhance deterrence beyond small nuclear arsenals.

### *Conventional Military Force & Prompt Global Strike*

Conventional military force has always played an important role in deterrence, and continues to do so today. Likewise conventional force could contribute to winter-safe deterrence. John Mueller has argued that memory of the massive destruction in World War II, caused mainly by conventional weapons, served as a powerful deterrent throughout the Cold War, rendering nuclear weapons unnecessary.[59] This argument suggests that conventional military force alone could offer a winter-safe deterrent. However, conventional military force has some limitations. Because conventional forces do not threaten massive destruction all at once, but instead harm incrementally, some suggest that conventional deterrence could result in more frequent, smaller conflicts.[60] Additionally, imbalances between different countries' conventional forces could cause geopolitical imbalances. The massive destructive force of nuclear weapons makes them a 'great equalizer' for any country that has them.[61] So while conventional military force will always have an important if imperfect role to play in a broader deterrence regime, it is important to pursue more powerful alternatives.

Conventional prompt global strike is a new technology that pairs high-speed, high-accuracy missiles with conventional bombs. The aim is to be able to strike anywhere in the world within one hour. Historically, only nuclear weapons could achieve this, but improvements in missile accuracy are making it possible to do the same with much smaller weapons. This new technology has already gained some consideration as a deterrent, including in recent remarks by Joseph Biden[62] and Vladimir Putin.[63] Because the conventional bombs are smaller, they are more suitable for threatening select military infrastructure, political leadership, or other small high-value targets, especially in time-sensitive situations such as the transfer of weapons of mass destruction.[64] They thus may only be capable of deterring smaller aggressions and can likewise only be one component of a broader deterrence regime.[65]

A major downside of conventional prompt global strike is its resemblance to nuclear missiles. A conventional strike could look the same as a nuclear strike to another country's radar systems, prompting that country to believe it is under nuclear attack and respond in kind.[66] This raises the risk of inadvertent nuclear war from false alarms mistaken as real. One proposed solution is to reserve ballistic missile trajectories for nuclear missiles and to only use guided trajectories for conventional prompt global strike. Another is to disclose the situations in which each type of missile would be used.[67] Such solutions can help, but the risk of inadvertent nuclear war would still be at least somewhat higher than it would be without any conventional prompt global strike. That said, the entire issue is avoided if nuclear weapons are no longer in use.

Conventional prompt global strike is also worrisome in its capability as a first-strike weapon, potentially capable of disabling the other side's deterrents, resulting in a destabilizing first-mover advantage.[68] Their first-strike potential at the heart of China's and Russia's concern about the American system under development: It someday may be able to knock out most of Russia's nuclear arsenal, perhaps with the rest of it being 'mopped up' by a missile defence system, thereby negating China's and Russia's deterrent and giving NATO a first-strike advantage, all without the harms and stigmas associated with the use of nuclear weapons.[69] While such concerns are inconsistent with the present American/NATO plans, a large arsenal conventional prompt global strike arsenal—perhaps thousands of weapons—may someday be able to achieve this.[70] This type of concern is important to address as conventional prompt global strike systems start to go live. Indeed, imbalances in conventional prompt global strike capabilities between countries could even be an impediment to nuclear disarmament.[71]

### *Neutron Bombs*

Neutron bombs, formally called enhanced radiation weapons, are fission-fusion nuclear bombs, typically with low yields, designed to release neutrons instead of absorb them into the explosion. The net result is that a high proportion of the bomb's energy is released as radiation relative to blast and heat.[72] Neutron bombs were initially conceived by American physicist Samuel Cohen as tactical weapons with minimal damage to civilians, infrastructure, surviving soldiers, and the environment. The idea was to detonate the bombs at an altitude of about 900m, such that only the neutron radiation would reach the surface, killing people within about a half-kilometre radius.[73] Neutron bombs were most heavily discussed in the late 1970s after American plans for their procurement caused a public controversy, especially in West Germany, where they were to be deployed, with deployment eventually deferred by Jimmy Carter.[74]

The characteristics of neutron bombs make them relatively well suited to tactical use. Neutrons are absorbed by air, with concentrations decaying by distance-cubed,[75] making the weapons able to hit smaller, more precise targets. Additionally, forces using neutron bombs can shield themselves from the neutrons behind thick layers of concrete or earth.[76] Indeed, the 1970s NATO deployment plan was mainly aimed at countering a possible Warsaw Pact tank invasion from East to West Germany.[77] However, the weapons could potentially also be aimed at cities for strategic deterrence, though this application has received less attention.

Compared to other nuclear bombs, neutron bombs have some potential to be more winter-safe. Because they produce more radiation relative to blast and heat, they can cause more harm to populations with less fire and smoke and thus less nuclear winter.[78] For ground bursts, the difference is not large enough to come close to bridging the gap between current arsenals and winter-safe arsenals, in which case neutron bombs could still only be one component of a winter-safe arsenal, though it could mean a somewhat higher limit on the number of nuclear weapons. For air bursts, minimal heat and blast would reach the surface, potentially avoiding any significant fire and smoke. If countries could commit to only using neutron bombs at altitude, then they might succeed as winter-safe deterrents. However, this would leave some risk of countries not following their commitments, which could result in nuclear winter.

One potential drawback of this usage of neutron bombs is that it only targets people and not infrastructure. This was at the heart of the 1970s controversy. The idea that the bombs would kill people while leaving infrastructure intact fuelled narratives of capitalism as caring only about property and not people.[79] West German politician Egon Bahr called the neutron bomb ‘a symbol of the perversion of thought’.[80] Another potential drawback is the possibility for civil defence. Bomb shelters and some regular buildings may offer enough shielding from neutrons to keep people safe. A country expecting a second strike attack could instruct its citizens to take appropriate shelter, thereby rendering the neutron bombs harmless.

*Biological and Chemical Weapons*

Biological and chemical weapons are typically grouped with nuclear weapons as the three main weapons of mass destruction, but in some ways they are very different. One important difference is that biological and chemical weapons are banned by international treaty. And for good reason: They not only can cause extensive, indiscriminate death and injury, but they can do so in an especially horrific fashion, leaving a disproportionate psychological toll.[81] The Biological and Chemical Weapons Conventions must be considered among the greatest successes of the international community. Many people would probably rather not even consider rescinding these conventions to re-proliferate these weapons. But as bad as they are, nuclear winter means that nuclear weapons can be even worse. The exception is contagious biological weapons, which could also cause global catastrophe and thus would not qualify as a safer deterrent; more on this below.

As unpleasant as it may be to consider, biological and chemical deterrence does have a certain logic to it. Like nuclear weapons, biological and chemical weapons can cause large and indiscriminate harm to populations, though perhaps to varying degrees.[82] Like nuclear weapons, biological and chemical weapons also cause a fear that goes beyond the physical harm that they cause. There is something extra about these three types of weapons that give them a major stigma, to the point of even being considered taboo.[83] To the extent that these weapons cause additional fear, as they clearly did after the 2001 anthrax attacks,[84] it only makes them more powerful as a deterrent.

The big advantage that chemical weapons and some biological weapons have over nuclear weapons is that their effects are mainly local. Because of this, they cannot cause a global catastrophe.[85] There is no chemical or biological equivalent to nuclear winter. Chemical or biological weapons could potentially spread worldwide, just as some toxic chemical pollutants do,[86] though they would diffuse to lower concentrations along the way, such that an extremely large amount of the weapons would be needed to cause significant global harm. The important exception is the contagious biological agents, like weaponized smallpox or Ebola. These can spread widely, causing global catastrophe of the same severity as nuclear winter.[87] While the spread can potentially be limited by mass vaccination, this would limit the weapons' potential as deterrents. Either way, the global risk is sufficient that contagious biological agents should not be considered as a safer substitute for nuclear weapons. But non-contagious biological toxins like ricin or anthrax could be considered.

Non-contagious biological toxins are more promising as deterrents than chemical weapons because they are higher density, in the sense of packing more potency per unit mass or volume.[88] Higher density could make these weapons more suitable to delivery on second-strike missile systems, an important attribute for a deterrent. Indeed, biological weapons (contagious and non-contagious) may be the only technology currently available besides nuclear weapons that could be used as a deterrent threatening widespread civilian casualties.[89]

A serious drawback of chemical and biological weapons as deterrents is the potential for civil defence. If a certain chemical or biological attack is expected, populations can be shielded with gas masks, vaccinations, secure airtight facilities, and other measures.[90] This shifts the military advantage to surprise first-strike attacks, since retaliatory second-strike attacks would not be a surprise and could be defended against. The net effect is to destabilize the geopolitical order: With large incentive for first-strike attacks and limited fear of retaliation, war becomes more likely.[91] While some civil defence is also possible for nuclear attacks,[92] the opportunities are more limited. A deterrence regime based on chemical and biological weapons would benefit from weapons that defeat civil defence measures. For example, the Soviet Union previously developed chemical weapons that went through gas masks.[93] These sorts of technologies would make chemical and biological weapons more viable as deterrents. Alternatively, states could announce the possession of unspecified types of chemical or biological weapons. Uncertainty about the type of weapon reduces the efficacy of civil defence[94] but could also reduce the credibility of the deterrent.

A related drawback is the latency period of biological weapons. Because the effects of the weapons are not immediately apparent, it may be feasible for biological attacks to be conducted anonymously. This further shifts the advantage to first strike attacks, because the victim country would not know whom to retaliate against.[95] Attacks could potentially even be done as spoofs designed to look like they came from some other country. To some extent, the potential for anonymous attacks and spoofing exists for nuclear weapons as well,[96] though the problem may be larger for biological weapons due to their latency period.

Another important factor is that chemical and biological weapons are a much greater proliferation risk than nuclear weapons. They are relatively easy and affordable to produce, and indeed are sometimes known as 'the poor man's atomic bomb'.[97] They can also be produced in facilities that appear benign, as seen for example in confusion over the Al-Shifa pharmaceutical factory in Sudan, which the United States destroyed in 1998 under suspicion of it producing chemical weapons.[98] The challenge is even greater for biological weapons, which can be produced at relevant scales in smaller facilities that are harder to distinguish from benign activities. Still, experience with compliance with the Biological Weapons Convention suggests that monitoring proliferation, while difficult, is also not impossible.[99] The technical skill needed for producing biological weapons suggests further non-proliferation options.[100] If biological or chemical weapons become a deterrent of choice, it could dramatically raise the prestige and lower the stigma attached to these weapons, inspiring more countries and nonstate actors to seek them. On the other hand, it could also increase the attention given to limiting their proliferation. It is thus unclear exactly how proliferation would be affected by these weapons becoming important deterrents. Further clarity on proliferation should inform any decision making about using chemical or biological weapons as deterrents.

Finally, chemical and biological weapons harm human bodies only—they do not destroy physical infrastructure. Because of this, they are singularly undesirable deterrents (potentially alongside neutron bombs detonated at altitude). All else equal, it would be vastly preferable to deter by threatening infrastructure than by threatening people. But all else may not be equal: Threats to infrastructure or people may be more or less successful deterrents in particular situations. Nuclear weapons of course threaten both, and so it is hard to know which is more important from our experience with nuclear deterrence. One should hope that deterrence does not require threatening mass death and injury. But if it does, chemical and non-contagious biological toxins may be preferable to nuclear or contagious biological weapons. All of them are highly destructive and horrific, but only the former do not risk global catastrophe.

### *Cyber Weapons*

Relative to chemical and biological weapons, cyber weapons and electromagnetic weapons (discussed below) are at the opposite end of the spectrum: They only threaten infrastructure, not people, or at least not people directly. Large destruction of infrastructure will inevitably cause indirect harms to people, as vital systems fail to provide crucial services. These indirect harms can potentially be quite large, and are important to consider, even though the primary damage is to physical infrastructure.

Cyber weapons work by hacking, infecting, or otherwise corrupting computer systems. Cyber weapons can be used for military and economic espionage, which can help developing countries catch up with more technologically advanced countries.[101] Cyber weapons can also be used for sabotage, as in the 2007 attack on Estonia, the 2008 attack on Georgia, and the 2010 Stuxnet virus infecting Iran's nuclear infrastructure.[102] While none of these were intended as deterrents, they do demonstrate the general viability of cyber attacks, just as Hiroshima and Nagasaki demonstrated the viability of nuclear attacks.

The potential deterrent value of cyber weapons comes from infiltrating and threatening critical systems such as those for water, transportation, telecommunications, and transportation.[103] If one country can use cyber attacks to successfully gain some degree of control over another country's critical systems, then it can threaten to cause those systems to malfunction or shut down. This is a significant threat, especially when the threatened country is highly reliant on computer systems. Such threats presumably hold at least some deterrence value.

However, cyber weapons have several important limitations as deterrents. One is the need for secrecy. As soon as it is known what type of cyber attack is imminent, threatened systems can be backed up, shut down, or otherwise defended.[104] Even highly sophisticated attacks like Stuxnet hinged on certain security holes that, once known, were easy to close.[105] As with biological and chemical weapons, this makes for an awkward deterrent, as one can only make vague threats of unspecified cyber attacks.

Another important limitation of cyber weapons is the difficulty of attribution. Most cyber attacks are never conclusively attributed to their attacker. Attribution has not even been conclusively made for the 2008 attack on Georgia, which coincided with early phases of the Russia-Georgia war. Russia is widely suspected, but definitive attribution has been elusive.[106] Most troubling is the potential for spoofing, in which an attacker makes it appear that the attack was perpetrated by someone else.[107] The difficulty of attribution makes cyber attacks very hard to deter, creating first-strike advantages. It also makes for a chaotic and unstable deterrent: Someone threatening a cyber attack is vulnerable to be blamed in a spoof, especially if the threat is for a nonspecific cyber attack (recalling the ease of defending against known cyber attacks).

A third limitation is the possibility that cyber weapons could attack command and control systems. If they can, then they could be used as first strike weapons, to the detriment of strategic stability. On the other hand, countries are very likely to attempt protecting their command and control systems from cyber attacks, to the extent that they can. That said, these three limitations would need to be overcome if cyber weapons are to be viable as deterrents. At this time, cyber weapons are not promising deterrents.

*Electromagnetic Weapons*

Electromagnetic weapons send out electromagnetic radiation (often known as an electromagnetic pulse, or EMP) that couples with and destroys electrical equipment—and only electrical equipment. The radiation passes harmlessly through human bodies.[108] The only physical harm to humans would come from the indirect consequences of losing electrical equipment. To be sure, the indirect consequences could be quite severe, given widespread dependence on electrical systems.[109] Some have even imagined desperate worst-case scenarios of widespread death and the few survivors struggling to cope with a world they are ill prepared for.[110] While very limited research has been conducted on electromagnetic weapons, some initial insights can be gained from what research is available.

The most destructive existing electromagnetic weapon is simply a nuclear weapon detonated at high altitude, at least 40km and ideally at least 112 km above the surface.[111] At such altitudes, gamma rays from the detonation interact with Earth's magnetic field, sending a pulse of electromagnetic radiation towards the surface.[112] A single large nuclear weapon could affect a very wide area, potentially even the whole of a large country, though the strength of the radiation diminishes with distance from the explosion.[113] This wide coverage makes nuclear electromagnetic weapons potentially viable for major geopolitical deterrence.

A deterrence regime based on electromagnetic pulses from nuclear weapons would alter the previous discussion of winter-safe nuclear arsenal limits. The high-altitude nuclear explosions needed for electromagnetic pulses do not burn cities, and thus cannot cause nuclear winter. In principle, arsenals can be arbitrarily large without risking nuclear winter, as long as the weapons are designated for high-altitude detonation. One would of course need to ensure that the weapons actually are used at high altitudes and not at cities. But that could be a moot point, due to the very broad coverage possible from a single high-altitude detonation, which reduces the need for large arsenal sizes. An arsenal of just a few large nuclear weapons, appropriately protected to ensure second-strike capabilities,[114] may be a sufficient deterrent even against major geopolitical adversaries. Such an arsenal is consistent with a global 50 weapon limit.

It is also possible to make electromagnetic weapons that are not based on nuclear weapons. Two types of non-nuclear electromagnetic weapons currently exist: high-powered microwave weapons and electromagnetic bombs driven by conventional explosives. However, these devices have much smaller ranges, up to about one mile.[115] Such a small range makes them poorly suited for large-scale deterrence, though they may be useful in select tactical situations. If non-nuclear electromagnetic weapons are desired for large-scale deterrence, new technologies would likely be needed.

Some defence against electromagnetic weapons is possible. Electrical equipment can be shielded.[116] However, it may be prohibitively expensive or even technologically infeasible to shield significant portions of a nation's electrical equipment, which means that civil defence is unlikely to nullify the weapons' deterrence value. An important question is whether command and control systems can be shielded. If they cannot be, then electromagnetic weapons could be used in a first strike, thereby reducing strategic stability and rendering electromagnetic weapons less suitable for deterrence.[117]

Meanwhile, civil defence to aid survivors is readily feasible. Countries can stockpile food, fuel, and other basic resources. Such stockpiles are expensive, but they are also valuable across a broad range of other catastrophe scenarios.[118] In addition, aid from other countries would be possible. An electromagnetic attack would harm infrastructure only in the area being attacked. Countries elsewhere around the world would remain intact and could step in with humanitarian assistance. The net effect could be an attack that massively harms a country's infrastructure but with relatively minimal harm to its citizens, making for a relatively humane deterrent. But the impacts of electromagnetic attacks have not been adequately studied, and further research is recommended before reaching any definitive conclusions.

Electromagnetic weapons also appear viable for retaliatory second-strikes. It would be generally viable to shield the weapons themselves from an incoming electromagnetic attack, keeping them available for second-strike,[119] as long as command and control systems could also be shielded. Furthermore, unlike cyber weapons, attribution and secrecy are not significant factors, at least not more than for any other type of weapon, including nuclear weapons detonated at ground. A country can announce its electromagnetic deterrent without diminishing its military efficacy. Overall, electromagnetic weapons appear to be generally attractive deterrents.

One potential downside of electromagnetic weapons is that it shifts strategic advantage towards those countries that are more capable or more willing to withstand electromagnetic attacks. While shielding infrastructure from the attacks would be difficult and expensive, doing so would be more feasible for wealthier countries. On the other end of the spectrum, less technologically advanced countries may be more able to withstand an attack, because they have less electrical equipment exposed. The countries with the most to lose would be countries with limited wealth yet significant electrical infrastructure.

## Discussion and Conclusion

No other weapon offers the same capacity of nuclear weapons for threatening massive destruction to both humans and infrastructure. To the extent that deterrence must threaten both, large nuclear arsenals may need to be replaced by a combination of other weapons, perhaps supplemented by small nuclear arsenals. Ideally, deterrence would not need to threaten massive destruction to humans, and could succeed with minimal loss of life. While the biological and chemical weapons stigmas and the 1970s neutron bomb controversy suggest some public hostility towards weapons that only threaten humans, this does not necessarily diminish (and could even enhance) these weapons' deterrence value.

The initial analysis presented above suggests that, for threatening widespread destruction of infrastructure with limited loss of life, electromagnetic attacks using nuclear weapons or novel technologies hold the most potential. However, the societal consequences of electromagnetic attacks have not been studied in adequate detail and may be quite harsh. For threatening massive destruction to humans, the most promising options are neutron bombs detonated at altitude and non-contagious biological toxins. However, neutron bombs could cause nuclear winter if detonated at ground, and potentially could be rendered harmless by civil defence. Non-contagious biological toxins are banned by treaty and widely deplored. Lifting their stigma poses a major proliferation risk that could destabilize the international community. Developing non-contagious biological toxins might increase the risk that contagious biological weapons would also be developed. Additional issues of political acceptability have also not been addressed in this paper. These risks and issues might be so large that the world would be better off with the risk of nuclear winter. But then again, they might not—nuclear winter is that large of a risk. While any conclusions about winter-safe deterrence must at this time be tentative, winter-safe deterrence does appear feasible. It would additionally be desirable for shrinking or eliminating the risk of catastrophic nuclear winter.

Several other factors are important to the decision of whether large nuclear arsenals should be replaced with winter-safe deterrents. One is the time it would take to make the switch. Making the switch would require significant time for planning, selecting the best options, procurement of new weapons systems, revising security doctrine, retraining personnel, and other activities.[120] If the switch to winter-safe deterrents would be slow relative to nuclear disarmament, then there would be no point in switching.

Another important factor is the probability that the weapons would be used. Nuclear weapons have a high threshold for use; replacing them with less destructive weapons could tempt countries to use their weapons more often, and could additionally lead to more provocative behaviour in general. This prospect raises a difficult question: Would humanity be better off with more frequent, smaller wars, or with a smaller chance of one large war that humanity may never recover from? The ethics of global catastrophic risk suggest that humanity would be better off with more frequent, smaller wars, because these wars would still permit human civilization to carry on. But this is small comfort to the people who might die in the smaller wars, and it is they (or their leaders) who usually make the decision.

A third important factor is the opportunity cost of the effort it could take to persuade countries to switch to winter-safe deterrents. The effort would need to be made by politicians, activists, scholars, and others; this effort could instead be directed elsewhere. Potentially, other efforts could be more effective at reducing nuclear winter risk, such as efforts to resolve the issues already identified as needed for achieving deep cuts,[121] promoting the idea that nuclear deterrence is not needed in the first place,[122] promoting the humanitarian consequences of nuclear weapons,[123] preparing to survive nuclear winter,[124] or working towards non-adversarial relations between nuclear weapon states.[125] These other efforts have additional appeal in that they do not involve promoting any weapons. However, for reducing nuclear winter risk, a broad suite of approaches may be most helpful.

Finally, winter-safe deterrence does not address the other reasons that states may have for keeping large nuclear arsenals, including military use, national pride, and international status. These other reasons are also important to address in identifying politically acceptable means of reducing nuclear arsenals to winter-safe levels. Future research on how to accomplish this is warranted, towards the ultimate goal of identifying weapons systems that are both desirable to today's nuclear weapon states and safe from nuclear winter or other global catastrophe.

Taking all of these factors into consideration, while winter-safe deterrence does appear feasible and desirable, no definitive conclusions can yet be made. However, two overarching conclusions are clear. First, nuclear winter presents a grave risk to human civilization, a risk that will persist as long as some countries continue to hold large nuclear arsenals. Second, the project of reducing nuclear winter risk best proceeds in consideration of the reasons that nuclear weapon states have for retaining their large nuclear arsenals. Joint consideration of nuclear winter risk and nuclear weapons policy can point to policy options that address both issues. Such options are more likely to actually get implemented, and in getting implemented they keep humanity safer.

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