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Understanding the humanitarian consequences and risks of nuclear weapons

New findings from recent scholarship

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Foreword

Today, the risk of nuclear conflict is higher than it has been in decades. Geopolitical tensions, irresponsible nuclear threats and nuclear blackmail make the taboo against the use of nuclear weapons look increasingly fragile. In 2022, the famous Doomsday Clock was set to an unprecedented 90 seconds to midnight, which is the closest it has been since the Clock's experts started to assess the risk of nuclear war in 1947.

In such a precarious situation of heightened nuclear risks, it is even more essential for the international community to be fully aware of the catastrophic humanitarian consequences that any use of nuclear weapons, let alone a nuclear conflict, would bring to all humanity and to the world as a whole. Increased awareness and knowledge are the basis for the urgent global action to prevent any use of nuclear weapons. They are also necessary to make progress towards nuclear disarmament and to move away from the precarious security paradigm that is based on the threat with potentially global humanitarian consequences.

Over the past 15 years, the concern about humanitarian consequences and risks of nuclear weapons moved to the centre of the international nuclear weapons discourse. Austria was strongly engaged in the 'humanitarian initiative', which sought to promote facts-based discussions about these crucial perspectives. Several international conferences dedicated to the humanitarian consequences and risks issues took place, including two in Vienna in 2014 and 2022, which raised the awareness, the knowledge and sense of urgency of the international community considerably.

2014 Vienna Conference on the Humanitarian Impact of Nuclear Weapons – BMEIA, Außenministerium Österreich

2022 Vienna Conference on the Humanitarian Impact of Nuclear Weapons – BMEIA, Außenministerium Österreich

The international conferences and the subsequent increased global discussions were in part stimulated by significant new knowledge about the humanitarian impact and risks of nuclear weapons and in part they sparked further research into these areas. The result is a growing body of scholarship that builds upon past knowledge but has significantly broadened the scope of research and yielded significant new findings. The gist of this research is that the humanitarian consequences of nuclear weapons are more complex, more serious and potentially catastrophic on a global and existential level. The same goes for the complexity of risks associated with nuclear weapons.

The breadth of new scholarly research contains many findings that warrant urgent policy consideration at an international level. Nevertheless, there is still contestation around this issue with some stakeholders claiming that there is nothing "new" in the research about the humanitarian impact of nuclear weapons despite compelling evidence to the contrary.

For this reason, the Austrian Federal Ministry for Europe and International Affairs has commissioned Dr Nick Ritchie and his team at the University of York to produce this overview of some of the most significant recent peer-reviewed scholarship about the humanitarian consequences of nuclear weapons explosions and the risks related to these weapons. The summary briefings are not a complete catalogue of recent research. They are intended as an overview for states and other interested stakeholders in order to stimulate a factual international discussion about the policy implications that should be drawn from this new evidence.

It took a long time for the scholarship on and the warnings about climate change to lead to global policy responses to address this existential threat. It is high time to see this happening much more on the continuing existential threat posed by nuclear weapons.

Ambassador Alexander Kmentt,
Director for Disarmament, Arms Control and Non-Proliferation at the Austrian Federal Ministry for Europe and International Affairs, July 2023

Introduction

We have learnt a lot about the humanitarian consequences and risks of nuclear violence over the past 10 to 15 years of the 'humanitarian initiative' on nuclear weapons. This series of briefings collated in this single report summarises the wide-range of new scholarship on these issues over this period. The scholarship is based on empirical analysis of what *has* happened, for example the atomic bombings of Hiroshima and Nagasaki, the effects of nuclear testing, close-calls and accidents, and nuclear doctrine and decision-making. It is also based on modelling and simulations of what *could* happen, for example assessments of the risk of nuclear war in a much-changed global technological and political context, the human fatalities and environmental effects of nuclear war, and the social effects of the detonation a single 10 kiloton terrorist nuclear device. Further simulations include the capacity of national international humanitarian and health agencies to respond to nuclear use scenarios, and food production in nuclear winter scenarios.

A substantial body of knowledge has therefore been produced over the past 10 to 15 years that reinforces three increasingly unassailable conclusions:

- Nuclear war would be a catastrophe with cascading consequences that potentially scale all the way to collapse of human civilisation.
- The risk of nuclear war is non-zero, becoming more complex, and claims to be able to manage and control that risk are illusory.
- Claims about the benefits of nuclear deterrence that justify the risks of shared catastrophe are empirically contested and shown to be contingent.

Dr Nick Ritchie and Mikhail Kupriyanov at the Department of Politics, University of York, have prepared a set of briefings summarising the findings of this scholarship under the following headings:

1 Nuclear risk:

1.1 Assessing the risk of nuclear violence
1.2 Artificial intelligence and nuclear risk
1.3 Luck, close calls and entanglement
1.4 Psychology and nuclear decision-making
1.5 Catastrophic risk and complexity

2 Consequences of nuclear violence:

2.1 The environmental effects of nuclear detonations
2.2 The humanitarian effects of nuclear detonations
2.3 Feeding the world in a nuclear winter
2.4 The effects of and responses to a 10kt nuclear detonation

1.1 Assessing the risk of nuclear violence: This briefing highlights findings on the efficacy of nuclear deterrence and the risk of nuclear war from new statistical methods applied to old and new datasets.

1.2 Artificial intelligence and nuclear risk: This briefing by Dr James Johnson (University of Aberdeen) summarises findings on the growing complexity of conventional-nuclear military forces and the effects of Artificial Intelligence (AI) in shaping nuclear crises. This analysis is necessarily speculative but generates new insights into new issues affecting nuclear risk.

1.3 Luck, close calls and entanglement: This briefing sets out new findings on historical cases of nuclear weapons accidents and close-calls, notably in crises between nuclear-armed states that reinforce the role of luck in non-nuclear detonation outcomes, and risks stemming from the entanglement of conventional and nuclear command and control systems.

1.4 Psychology and nuclear decision-making: This briefing highlights new findings on psychological processes of numbing, dehumanisation and victim blaming, socio-political and ideological biases, global information ecosystem and manipulation, and emotion, revenge, anger and humiliation in relation to nuclear weapons and decision-making.

1.5 Catastrophic risk and complexity: This briefing sets out new findings on the interconnectedness and complexity of global systems as a core feature of world politics. It explains how multiple nuclear detonations in a violent conflict are likely to have cascading effects across multiple global systems.

2.1 The environmental effects of nuclear detonations: This briefing presents the extensive body of work modelling the effects of soot-generating firestorms ignited by nuclear weapons detonations. This body of work explains how soot circulates through the upper atmosphere, reduces surface and ocean temperatures, and affects crop production, ozone depletion, fisheries, ocean acidification, etc.

2.2 The humanitarian effects of nuclear detonations: This briefing summarises new research on the effects of nuclear weapons detonations on human bodies and societies, including the Hiroshima and Nagasaki bombings, nuclear testing, the capacity of the international humanitarian system to respond, and fatalities in a range of nuclear war scenarios.

2.3 Feeding the world in a nuclear winter: This briefing summarises research on the possibilities for feeding the global population using 'alternative foods' in disaster scenarios in which sunlight is blocked for many years, including a nuclear winter.

2.4 The effects of and responses to a 10-kiloton nuclear detonation: this briefing sets out findings from a new body of work in the US on the effects of and responses to a 10 kt nuclear detonation in a major US city through detailed modelling.

Further research

This body of work suggests areas of further research that build on the findings set out in the briefings:

1. Modelling the cascading effects of multiple nuclear detonations on social, environmental and economic systems in an era of 'global polycrisis' and the causal relationships between major power war and polycrisis. This would build on research on cascading disasters, global systemic risks, the effects of a 10 kt nuclear detonation in the United States, and modelling of the environmental effects of a range nuclear war scenarios to date.
2. Identify and investigate additional cases in nuclear-armed states where luck can be shown empirically to have played a role in non-nuclear detonation outcomes.
3. Further research on the interaction of AI, cyber technologies, information awareness, speed of decision-making, misinterpretation and crisis decision-making in crises in which the use of nuclear weapons is plausible.
4. Investigate what nuclear-armed states claim to know and to have known about the effects of nuclear detonations through their responses to major national and international studies on the effects of nuclear war[1], and through their own studies and modelling on the effects of nuclear detonations and how such studies correspond to the models and conclusions in the open scientific literature.

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1 Such as: Vulnerabilities of Social Structure: Studies of the Social Dimensions of Nuclear Attack (US Office of Civil Defense, 1966); The Effects of Nuclear War (US Office of Technology Assessment, 1979); The Effects on the Atmosphere of a Major Nuclear Exchange (US National Research Council, 1985), The Effects of Nuclear War on Health and Health Services (World Health Organization, 1987); Comprehensive Study on Nuclear Weapons (United Nations General Assembly, 1980); and Study on the climatic and other global effects of nuclear war (United Nations General Assembly, 1988).

5. Further research on the relationship between biological sex and radiation harm, why sex difference in radiation harm is greatest in young children, and the ways in which regulation of radiation exposure has privileged male bodies and the consequences of doing so.
6. Systematic study and modelling of the humanitarian and environmental legacies of nuclear weapons testing, global and national policy responses to these legacies, and the relationship between rights, law and nuclear harms.
7. Further research on the psychological characteristics of leaders of nuclear-armed states and their approaches to crisis, risk and brinkmanship, and the relationship between leadership dispositions and organisational and strategic cultures in interpreting and responding to violent inter-state crises.

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1 Nuclear risk

ASSESSING THE RISK OF NUCLEAR VIOLENCE

1.1 Assessing the risk of nuclear violence

Assessing the risk of nuclear war is difficult, but new research over the past 15 years has investigated the question in much more detail. It is important to note that the risk of the use of nuclear weapons is *greater than zero*. Deterrence can fail and nuclear-armed states have well-developed plans and capabilities for the rapid use of nuclear weapons. The question is what is the *level* of risk?

A number of studies have addressed this question and their findings show that there are multiple pathways to nuclear use and nuclear war based on historical precedent and that, whilst there are difficult challenges with assigning accurate probabilities, even a very low annual probability of nuclear use builds up over time to a significant level that is often denied or downplayed by nuclear-armed states. In sum, these probabilistic analyses show that there is a continuous risk of nuclear use that builds up over time to a significant probability of nuclear detonations and nuclear war.

A number of recent quantitative statistical studies have examined claims about nuclear deterrence and how certain and effective it is. They use existing databases on conflict between states and they compare patterns of conflict involving nuclear-armed states and nuclear-armed states and non-nuclear-armed states against conflicts involving only non-nuclear-armed states. The results of these studies are mixed and this scholarship *does not* support the type of unequivocal claims about nuclear deterrence that its supporters routinely make.

These studies show some support for the argument that nuclear weapons tend to reduce the probability of war and constrain crisis behaviour, but the scholarship as a whole offers no *definitive* conclusion. The major outlier is the 1999 Kargil war between nuclear-armed India and nuclear-armed Pakistan. In addition, these studies suggest that nuclear deterrence can require leaders to get closer to the brink of disaster through conflict escalation in order to make their deterrent threat more credible.[1]

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1 This scholarship draws on an earlier wave of statistical analysis in the early 1990s, including:
Randolph M. Siverson & Ross A. Miller (1993) The escalation of disputes to war, *International Interactions*, 19:1-2. **Link:** https://doi.org/10.1080/03050629308434820: shows that disputes between nuclear-armed states have a 7 x *greater probability of escalating to conflict short of war* than do disputes involving non-nuclear-armed states.
Huth, P., Bennett, D. S., & Gelpi, C. (1992). System Uncertainty, Risk Propensity, and International Conflict among the Great Powers. *The Journal of Conflict Resolution*, 36: 3. **Link:** http://www.jstor.org/stable/174344: shows that the possession of nuclear weapons by great powers does not deter a challenger from initiating a militarised dispute based on 97 cases of the escalation of deterrence encounters among great powers from 1816 to 1984.
Geller, D. S. (1990). Nuclear Weapons, Deterrence, and Crisis Escalation. *The Journal of Conflict Resolution*, 34: 2. **Link:** http://www.jstor.org/stable/174196: also shows that nuclear-armed states have a substantially higher probability of escalating a dispute, short of war, than do non-nuclear-armed states.

A third smaller set of empirical studies has examined the maximum number of nuclear weapons that could be detonated whilst avoiding a 'nuclear winter' scenario (see briefing 2.3) and shows the level is orders of magnitude below the current level of global nuclear armament.

Probabilistic analysis of nuclear war

Lundgren, C. (2013): 'What are the Odds? Assessing the Probability of a Nuclear War', *The Nonproliferation Review.* 20: 2, 361-374.
Link: https://doi.org/10.1080/10736700.2013.799828.

Carl Lundgren is a US economist. He looked at the probability of nuclear war arising from three broad scenarios: 1) an international crisis leading directly to nuclear war; 2) an accident or misperception leading to nuclear use; and 3) an escalation of a conventional war to nuclear use. Lundgren concludes that the risk of nuclear war during the 44 years of the Cold War (1945-1989) was 44.3% based on evidence of nuclear crises and mishaps.

He then calculates that the first 66 years of the nuclear age (1945-2011 when he conducted the research) produced a 61% chance of a nuclear war. Lundgren states that this is equivalent to a 2.1% chance per year, or an average frequency of one nuclear war every 47 years. Lundgren concludes that "Fighting the Cold War with nuclear armaments and nuclear threats was a perilous wager. The probability of a failure resulting in nuclear war exceeded the probability of making an incorrect call while flipping a coin" (p. 373).

Hellman, M. (2008). Risk analysis of nuclear deterrence. *The Bent of Tau Beta Pi.*
Link: https://www.tbp.org/pubs/Features/Sp08Hellman.pdf.

Martin Hellman is a US cryptologist, mathematician and Professor Emeritus of Electrical Engineering at Stanford University. He uses probabilistic risk analysis (PRA) methods to assess the failure rate of nuclear deterrence. Hellman argues that the failure rate for nuclear deterrence should be *at least* that of the design requirement for a failure rate for a significant release of radioactivity for nuclear reactors of less than 10^{-6} (0.0001%) per reactor per year.

He uses a 'Cuban Missile Type Crisis' (CMTC) to estimate the failure rate of deterrence but he warns that this model underestimates the probability of failure because it doesn't take into account other events that could lead to nuclear use, such as command-and-control malfunctions and nuclear terrorism. Hellman calculates the upper annual probability of a CMTC resulting in a nuclear world war as 1% and the lower probability as 0.01%. Lundgren makes the crucial point that even this lower annual estimate is still much *higher* than a design failure rate of less than 0.0001% for a nuclear reactor resulting in a significant release of radioactivity. The conclusion is that we are prepared to accept a much greater risk of nuclear war than we are for a major nuclear reactor accident.

Barrett, A., Baum, S., & Hostetler, K. (2013). Analyzing and Reducing the Risks of Inadvertent Nuclear War Between the United States and Russia. *Science & Global Security*. 21, 106-133.
Link: https://scienceandglobalsecurity.org/archive/sgs21barrett.pdf

Baum, S., de Neufville, R., & Barrett, A., (2018). A Model for the Probability of Nuclear War'. Global Catastrophic Risk Institute. Working Paper 18-1.
Link: https://gcrinstitute.org/papers/042_nuclear-probability.pdf

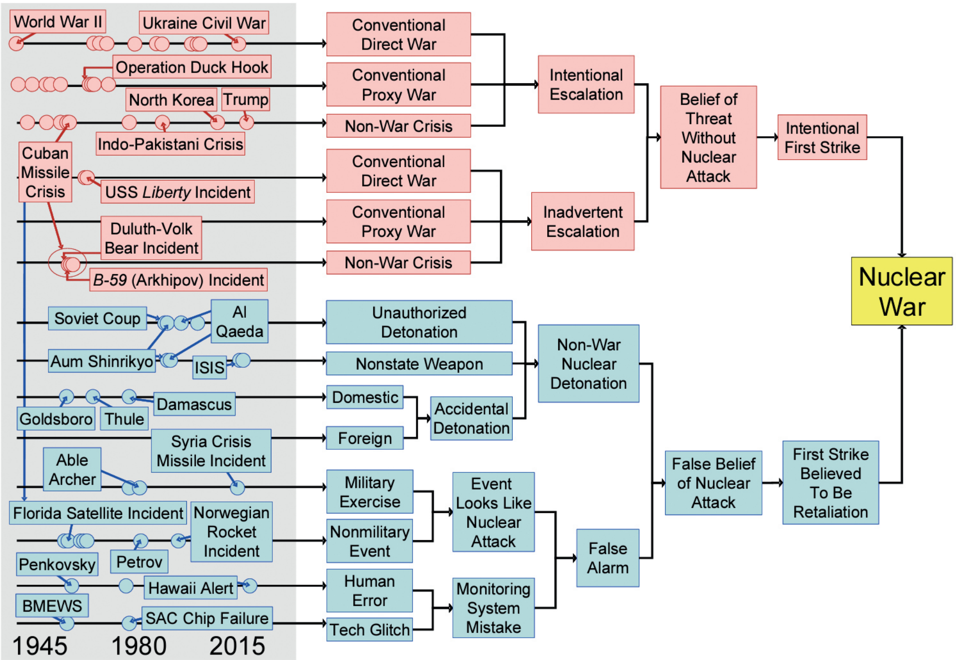
Baum, S., & Barrett, A. (2018). A Model for the Impact of Nuclear War. Global Catastrophic Risk Institute. Working Paper 18-2.
Link: https://gcrinstitute.org/papers/043_nuclear-impacts.pdf

Seth Baum and his colleagues at the Global Catastrophic Risk Institute have looked carefully at the probability of nuclear war. Baum, Barrett and Hostetler develop a probabilistic model to estimate the annual probability of the use of nuclear weapons by the US or Russia in response to mistaken indicators of attack by the other state. Their model produces an annual probability of 1% during periods of high US-Russia tension and 0.3% during periods of low tension.

In 'A Model for the Probability of Nuclear War', Baum, de Neufville and Barrett model 14 scenarios based on a review of historical incidents in which nuclear war threatened to occur. They model three types of event that could lead to nuclear use through intentional escalation or inadvertent escalation: 1) a direct conventional war; 2) a proxy conventional war; and 3) a non-war crisis (i.e., "a high-tension event that could lead to nuclear war without conventional war occurring first"). They use historical data on 60 historical near-miss incidents (incidents that went partway to potential nuclear war) to estimate probabilities.

They do not derive actual probabilities because of the limits of empirical data, but the scenarios they develop clarify our understanding of plausible pathways to nuclear detonations and nuclear war. Nevertheless, they make the vital point that "the probability of nuclear war occurring increases over longer periods of time" as a basic principle of probability irrespective of the initial estimate for the probability of occurrence. They provide illustrative examples based on the probability of there being at least one nuclear war. For example, if the probability of nuclear war occurring during a year is estimated at 1% (0.01), the probability of a nuclear war occurring over a decade is 9.5% (0.095) and the probability of a nuclear war occurring over a century is 63.2% (0.632).

The figure below shows the pathways they analyse. The shaded area is based on their historical incidents dataset, with select incidents labelled. The unshaded area is based on their scenario model.



Source: Figure 1 in Baum, S., de Neufville, R., & Barrett, A., (2018). A Model for the Probability of Nuclear War'. Global Catastrophic Risk Institute. Working Paper 18-1., p. 2.

Assessing the effectiveness of nuclear deterrent threats

Asal, V., & Beardsley, K. (2007). Proliferation and International Crisis Behavior. *Journal of Peace Research*. 44: 2. Link: https://doi.org/10.1177/0022343307075118

Beardlsey and Asal show that crises involving nuclear-armed states are *more likely to end without violence* and, as the number of nuclear-armed states involved increases, the likelihood of war continues to *fall*. They use the International Crisis Behaviour dataset of 434 international crises from 1918 to 2001.

Rauchhaus, R. (2009). Evaluating the Nuclear Peace Hypothesis: A Quantitative Approach. *Journal of Conflict Resolution*, 53: 2.
Link: https://www.jstor.org/stable/20684584?seq=1#metadata_info_tab_contents

Rauchhaus looks at military disputes between states from 1885 to 2000. He shows that 1) the probability of war drops significantly in conflicts involving two nuclear-armed states (supporting the theory of nuclear deterrence); 2) the probability of a crisis being initiated *and* the limited use of force between two states *increases* when both are nuclear-armed; and 3) when only one state is nuclear-armed, then the probability of being involved in a military conflict *and* the probability of a conflict escalating to war *increase*.

Beardsley, K., & Asal, V. (2009). Winning with the Bomb. *Journal of Conflict Resolution*, 53: 2. Link: https://doi.org/10.1177/0022002708330386

Beardlsey and Asal's statistical analysis shows that nuclear-armed states are more constrained in crises with other nuclear states compared to non-nuclear-armed states. However, the article also demonstrates that nuclear-armed states are just as likely to get involved in military crises as non-nuclear-armed states.

Gartzke, E., & Jo, D.-J. (2009). Bargaining, Nuclear Proliferation, and Interstate Disputes. *Journal of Conflict Resolution*, 53: 2. Link: https://doi.org/10.1177/0022002708330289

Gartzke and Jo find that the possession of nuclear weapons has *little effect* on the initiation of disputes by states. In other words, nuclear-armed and non-nuclear-armed states are not statistically deterred from initiating disputes with a nuclear-armed state.

Kroenig, M. (2013). Nuclear Superiority and the Balance of Resolve: Explaining Nuclear Crisis Outcomes. *International Organization*. 67: 1. Link: http://www.jstor.org/stable/43282155

Kroenig argues that 'nuclear brinkmanship theory' is statistically correct in that the state that is willing to run the greatest risk of nuclear war before submitting will be most likely to 'win' a nuclear crisis, *and* that the state with the largest nuclear arsenal ('nuclear superiority') will be willing to run the greatest risk. However, "states that escalate high-stakes nuclear crises are also more likely to experience accidental nuclear wars. Indeed, nuclear superiority provides a coercive advantage only because there is a real risk that events could spiral out of control and result in catastrophe".

Sechser, T. S., & Fuhrmann, M. (2013). Crisis Bargaining and Nuclear Blackmail. *International Organization*, 67: 1. Link: http://www.jstor.org/stable/43282156

In the same journal issue as Kroenig (article before), Sechser and Fuhrmann's statistical analysis shows that nuclear weapons or nuclear superiority offer *no coercive advantages* compared to non-nuclear-armed states, contradicting Kroenig's results. They use a new dataset of more than 200 'militarised compellent threats' from 1918-2002. Kroenig, Sechser and Fuhrmann debated their contradictory findings here:
https://www.duckofminerva.com/category/symposia/nuke-superiority

Bell, M. S., & Miller, N. L. (2015). Questioning the Effect of Nuclear Weapons on Conflict. *Journal of Conflict Resolution*, 59: 1. Link: https://doi.org/10.1177/0022002713499718
Bell & Miller's statistical analysis shows that nuclear-armed states are *neither more nor less likely to fight wars or sub-war conflicts* with each other than non-nuclear armed states are. At the same time, nuclear-armed states are *more likely* to initiate disputes against new opponents.

Risk and nuclear numbers

Pearce, J. & Denkenberger D. (2018). A National Pragmatic Safety Limit for Nuclear Weapon Quantities. *Safety.* 4: 2. Link: https://doi.org/10.3390/safety4020025

This study determines the maximum number of nuclear weapons that could be detonated whilst avoiding direct physical negative consequences sufficient to undermine national interests, specifically a 'nuclear winter' scenario. The study looked at the levels of starvation and economic impact for the best-case wealthy aggressor state with abundant arable land for scenarios involving the detonation of 7000, 1000, and 100 nuclear weapons of 15kt or greater explosive yield. The results found that the use of more than 100 nuclear weapons by any aggressor state (including those best placed to handle the consequences) even with optimistic assumptions (including no retaliation) would cause unacceptable damage to their own society. This is defined as "significant economic disruption of the aggressor nation and acute food insecurity for a significant fraction of the population" leading to the destabilisation of the society. Thus, 100 nuclear warheads is the pragmatic limit and use of government funds to maintain more than 100 nuclear weapons does not appear to be rational. This is based on the principle that "no country should have more nuclear weapons than the number necessary for unacceptable levels of environmental blow-back on the nuclear power's own country if they were used".

Baum, S. (2015). Winter-Safe Deterrence as a Practical Contribution to Reducing Nuclear Winter Risk: A Reply. *Contemporary Security Policy* 36:2, 387-397.
Link: https://doi.org/10.1080/13523260.2015.1054101

In this research, Baum calculates that the *worldwide* limit for nuclear arsenals to ensure that the nuclear winter scenario could *never* occur in the event that *all* available nuclear weapons were detonated in a conflict is 50 Hiroshima-sized weapons. He considers this a relatively low limit to err on the safe side and acknowledges that where to set the limit is highly uncertain given uncertainty about the impacts of nuclear winter. With only 50 total nuclear weapons, a severe nuclear winter catastrophe and permanent collapse of civilisation is very unlikely to occur, though some harmful nuclear winter effects could still occur.

ARTIFICIAL INTELLIGENCE AND NUCLEAR RISK: RETHINKING DETERRENCE STRATEGY IN THE AGE OF AI

The context for investigating and understanding the risks of nuclear violence has changed significantly over the post-Cold War period. It has become politically, economically and technologically messier and more complex, and ripe with uncertainties and asymmetries. A period of multipolarity is emerging in which a plurality of actors is becoming empowered as the era of US unipolarity declines. The nuclear bipolarity of the Cold War is giving way to nuclear multipolarity as nine nuclear-armed states consolidate their nuclear arsenals. Nuclear multipolarity is further complicated by new technologies that are forcing changes in how we think about the risks of nuclear violence. Analysis of the relationships between new technologies and nuclear risk is necessarily speculative, given that we have no data on nuclear war and how existing and emerging weapon systems and technologies will interact in a conventional and/or nuclear war. Nevertheless, scholars have examined these relationships and generated important insights.

One of those experts is Dr James Johnson, University of Aberdeen, who has looked in detail at the relationship between Artificial Intelligence, cyber and nuclear weapons and recently published a book on *AI and the Bomb: Nuclear strategy and risk in the digital age* (Oxford University Press, 2023). Given the challenges of producing empirical findings based on case study research in an area that is necessarily speculative, in this briefing Dr Johnson instead provides an overview of key issues based on his extensive research.

1.2 Artificial Intelligence and Nuclear Risk: Rethinking Deterrence Strategy in the Age of AI

Dr James Johnson, University of Aberdeen

We are in an era of rapid disruptive technological change, especially in AI.[1] AI technology is already fused into military machines, and global armed forces are well advanced in their planning, research and development, and, in many cases, deployment of AI-enabled capabilities.[2] Nuclear-armed great powers are investing political capital and financial resources in developing the field of artificial intelligence technology and AI-enhanced autonomous weapons systems, seeking to derive the maximum potential military benefits — at a tactical, operational, and strategic level — these systems offer.[3]

AI does not exist in a vacuum. In isolation, AI is unlikely to be a strategic game changer.[4] Instead, it will likely reinforce the destabilising effects of advanced weaponry, thereby increasing the speed of war and compressing the decision-making timeframe. The inherently destabilising effects of military AI may exacerbate tension between nuclear-armed powers, especially China and the United States (US), but not for the reasons you may think.

However, since we have yet to see how AI might influence deterrence, escalation, strategic stability, and crisis management in the real world — notwithstanding the valuable insights from experimental war gaming — the discourse is largely a theoretical and speculative endeavour. Nevertheless, there is little research that indicates how existing concepts of escalation, nuclear terrorism, and classical deterrence theories might apply (or be tested) in the digital age — increasingly defined by developments in AI and autonomy — where perfect information and rational decision making cannot be assumed.

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1 This discussion paper is adapted from sections of Johnson, J., (2023). *AI and the Bomb: Nuclear Strategy and Risk in the Digital Age* (Oxford University Press, 2023).

2 See Johnson, J., (2021). *Artificial Intelligence & the Future of Warfare: USA, China, and Strategic Stability* (Manchester: Manchester University Press); Horowitz, M., Scharre, P., and Velez-Green, A., (2017). *A Stable Nuclear Future? The Impact of Automation, Autonomy, and Artificial Intelligence* (Philadelphia, PA: University of Pennsylvania); Cummings, M.L., (2017). *Artificial Intelligence and the Future of Warfare* (London: Chatham House); Freedman, L., (2017). *The Future of War* (London: Penguin Random House); Allen, G. & Chan, T., (2017). *Artificial Intelligence and National Security* (Cambridge, MA: Belfer Center for Science and International Affairs); Ayoub, K. & Payne, K., (2016). "Strategy in the Age of Artificial Intelligence," Journal of Strategic Studies, 39, no. 5–6: pp. 793–819; Geist, E. & Lohn, A.J., (2018). *How Might Artificial Intelligence Affect the Risk of Nuclear War?* (Santa Monica, CA: RAND Corporation).

3 Johnson, J., (2019). "Deterrence in the Age of Artificial Intelligence & Autonomy: A Paradigm Shift in Nuclear Deterrence Theory and Practice?", *Defense & Security Analysis*, 36, no. 4: pp. 422–448.

4 James Johnson, "Artificial Intelligence in Nuclear Warfare: A Perfect Storm of Instability?" *The Washington Quarterly* 43, no. 2 (2020): pp. 197–211.

The Emerging AI-Nuclear Security Nexus

AI technologies are being researched, developed, and, in some cases, operationally deployed in the context of the broader nuclear deterrence architecture of early-warning and intelligence, surveillance, and reconnaissance; command and control; nuclear weapon delivery systems; and non-nuclear operations.[5]

Early-Warning and Intelligence, Surveillance, and Reconnaissance (ISR)

AI machine learning might quantitatively enhance existing early-warning and intelligence, surveillance, and reconnaissance systems in three ways.

1. Machine learning, in conjunction with cloud computing, unmanned aerial vehicles (or drones), and big-data analytics could be used to enable mobile intelligence, surveillance and reconnaissance platforms to be deployed in geographical long ranges, and in complex, dangerous environments. They can process real-time data and alert commanders of potentially suspicious or threatening situations, such as military drills and suspicious troop or mobile missile launcher movements.
2. Machine-learning algorithms could be used to gather, mine, and analyse large volumes of intelligence (open-source and classified) sources to detect correlations in a range of datasets, some of which might be contradictory, compromised, or otherwise manipulated.
3. Relatedly, algorithmic processed intelligence could be used to support commanders to anticipate — and thus more rapidly pre-empt — an adversary's preparations for a nuclear strike.

In short, AI could offer human commanders operating in complex and dynamic environments vastly improved situational awareness and decision-making tools, allowing more time to make informed decisions with potentially stabilising effects.[6]

Nuclear Command, Control, and Communications (NC3)

The impact of AI technology is unlikely to have a significant impact on nuclear command and control (C2) — which for several decades have synthesised automation but not autonomy. This is because the algorithms that underlie today's complex autonomous systems today are too unpredictable, vulnerable (i.e., to adversarial cyber-attacks), unexplainable (the "black-box" problem), and brittle to be used unsupervised in safety-

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5 Boulanin, V. (ed.), (2019). The Impact of Artificial Intelligence on Strategic Stability and Nuclear Risk Vol. I Euro-Atlantic Perspectives (Stockholm: SIPRI Publications).

6 Johnson, J. (2023). "Automating the OODA loop in the age of intelligent machines: reaffirming the role of humans in command-and-control decision-making in the digital age," *Defence Studies*, 23:1, pp. 43-67, DOI: https://doi.org/10.1080/14702436.2022.2102486

critical domains.[7] For now, there is a broad consensus amongst nuclear experts and nuclear-armed states that, even if the technology permitted[8], AI decision-making which directly impacts nuclear C2 functions (i.e., missile launch decisions), should not be pre-delegated to AIs.[9] Whether this fragile consensus can withstand mounting first-mover advantage temptations in a multipolar nuclear order, or human commanders viewing AI as a panacea for the cognitive fallibilities of human analysis and decision-making is an open question. [10]

- The UK Ministry of Defence (MoD) in its inaugural AI Strategy stated that it "will ensure that – *regardless of any use of AI in our strategic systems* – human political control of our nuclear weapons is maintained at all times" (emphasis added).[11] However, the UK MoD is also testing platforms for future AI-enhancement of pattern recognition, C2, and intelligence analysis. [12]
- The US Defense Department's Joint All-Domain Command and Control (JADC2) Strategy report stated that the US military "will leverage AI and machine learning to help accelerate the commander's decision cycle […] to adapt and modernise existing tactical, operational, and strategic C2 processes and capabilities," and integrate and collaborate these improvements with nuclear NC3 systems.[13]
- Open source analysis suggests that Russia is prioritising AI research and development in areas including C2, electronic warfare, cyber, and uncrewed systems across domains (including nuclear).[14]

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7 See Loss, R. and Johnson, J. (2019). "Will Artificial Intelligence Imperil Nuclear Deterrence," *War on the Rocks*, September 19, https://warontherocks.com/2019/09/will-artificial-intelligence-imperil-nuclear-deterrence/; Holland, A.M., (2021). *Known Unknowns: Data issues & Autonomous Military Systems* (Geneva: UNIDIR); and Johnson, Artificial Intelligence & the Future of Warfare, chapter 1.

8 Recent advances in ML and AI have already led to significant qualitative improvements to a broad range of autonomous weapon systems, resolving several technical bottlenecks in existing military technology. Ibid., p. 27.

9 For a notable exception, see Lowther, A. & McGiffin, C., (2019). "AMERICA needs a "Dead Hand,"' War on the Rocks, August 16, https://warontherocks.com/2019/08/america-needs-a-dead-hand/; and Field, M., (2019). "Strangelove Redux: US Expert Propose Having AI Control Nuclear Weapons," *Bulletin of the Atomic Scientists*, August 30, https://thebulletin.org/2019/08/strangelove-redux-us-experts-propose-having-ai-control-nuclear-weapons/.

10 See Watson, "The Rhetoric and Reality of Anthropomorphism in Artificial Intelligence," pp. 417–440; and Skitka, L.J., Mosier. K.L., & Burdick, M., (1999). "Does Automation Bias Decision-Making?" *International Journal of Human-Computer Studies* 51, no. 5: pp. 991–1006.

11 UK Ministry of Defence (2022), *Defence Artificial Intelligence Strategy* (London: Ministry of Defence, 2022), p. 59.

12 Ibid., p. 32.

13 US Department of Defense (2022), *Joint All-Domain Command and Control (JADC2) Strategy* (Washington DC: US DoD), p. 5.

14 Bendett, S., Boulègue, M., Connolly, R., et al. (2021). "Advanced military technology in Russia Capabilities, limitations and challenges" (London: Chatham House), www.chathamhouse.org/2021/09/advanced-military-technology-russia/06-military-applications-artificial-intelligence

- Open-sources also indicate that China leverages emerging technology including AI, big data analytics, quantum computing, and 5G to prepare its force for future "intelligentised" warfare at every level of warfare (including nuclear), and to enhance the People's Liberation Army's (PLA) dual-use (conventional and nuclear) C2 architecture.[15]

Nuclear Missile Delivery Systems

AI technology will likely affect nuclear weapon delivery systems in several ways:

1. Machine-learning algorithms may be used to improve the accuracy, navigation (pre-programed guidance parameters), autonomy ("fire-and-forget" functionality) of missiles, and precision — mainly used in conjunction with hypersonic glide vehicles. For example, China's DF-ZF manoeuvrable hypersonic glide vehicle is a dual-capable (nuclear and conventionally armed) prototype with autonomous functionality.16
2. It could improve the resilience and survivability of nuclear launch platforms against adversary counter-measures, such as electronic warfare jamming or cyber-attacks — that is, autonomous AI-enhancements would remove the existing vulnerabilities of communications and data links between launch vehicles and operators.
3. The extended endurance of AI-augmented unmanned (i.e., unmanned underwater vehicles and unmanned combat aerial vehicles) platforms used in extended intelligence, reconnaissance, and surveillance missions — that cannot be operated remotely — can potentially increase their ability to survive countermeasures and reduce states' fear of a nuclear decapitation. This is especially the case in asymmetric nuclear relationships, such as US-Russia, India-Pakistan, and US-China.

Nuclear Deterrence and AI

The post–Cold War literature is rich in scholarship on how technologically complex nuclear systems can cause technical (and human-related) accidents and false alarms, which are considered particularly escalatory where one side lacks confidence in its retaliatory (or second-strike) capacity.[17]

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15 US Department of Defense (2022), Military and Security Developments Involving the People's Republic of China 2022 (Washington, D.C.: US DoD).

16 Saalman, L. (2018). "China's Integration of Neural Networks into Hypersonic Glide Vehicles," in *AI, China, Russia, and the Global Order: Technological, Political, Global, and Creative Perspectives*, edited by N. D. Wright, White Paper (US Department of Defense and Joint Chiefs of Staff: Washington, D.C.), pp. 153–160.

17 Perrow, C. (1984). *Normal Accidents: Living with High-Risk Technologies* (New York: Basic Books).

During the Cold War, the perennial fear that an action or signal misinterpreted by the other side — in the context of uncertainty and incomplete information associated with modern warfare — could trigger nuclear pre-emption is a useful point of departure to consider AI and autonomy.[18] Accidental nuclear war — a nuclear confrontation without a deliberate and properly informed decision to use nuclear weapons on the part of the nuclear-armed state(s) involved — could be caused by a variety of accidents.[19] Most often, these encompass a combination of human error, human-machine interaction failure, and procedural or organisational factors. Moreover, despite paying lip service to Machiavelli's fortuna (the role of uncertainty in international affairs), decision-makers underestimate the importance and frequency of accidents and randomness in these interactions.[20]

Similar to historical cases where human-machine interactions have caused or compounded accidents involving complex weapon systems, AI-enhanced systems operating at higher speeds, increased levels of sophistication, and compressed decision-making timeframes will likely further reduce the scope for de-escalating situations and contribute to future mishaps. The rapid proliferation and ubiquity of advanced technologies, such as offensive cyber, hypersonic weapons, and AI and autonomous weapons will make it increasingly difficult for states to mitigate this vulnerability without simultaneously improving their ability to strike first, thereby undermining the survivability of others' strategic forces.

The size, mobility, hardening, and relatively hidden features of great powers' nuclear arsenals ensured their ability to withstand the first strike and deliver a retaliatory second strike, constituting the core pillars of Cold War era nuclear deterrence. As other disruptive technologies associated with the information revolution — particularly big-data analytics, robotics, quantum computing, nanotechnology, and cyber capabilities — advances in AI and autonomy threaten to upend this fragile arrangement in several ways.[21]

Vulnerability of Nuclear-Deterrence Forces

The integration of AI, machine learning, and big-data analytics can dramatically improve militaries' ability to locate, track, target, and destroy a rival's nuclear-deterrent forces — especially nuclear-armed submarines and mobile missile forces — without the need to

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18 Cimbala, S.J., (2022). *The Dead Volcano: The Background and Effects of Nuclear War Complacency* (Westport, Connecticut: Praeger).

19 Intriligator, M.D., and Brito, D.L., (1993). "Minimizing the Risks of Accidental Nuclear War: An Agenda for Action," in *Inadvertent Nuclear War*, edited by Hakan Wilberg, Ib Damgaard Petersen, and Paul Smoker (New York: Pergammon Press), pp. 221–237.

20 Jervis, R., (1976). *Perception and Misperception in International Politics* (Princeton, NJ: Princeton University Press).

21 Bracken, P. (2016). "The Cyber Threat to Nuclear Stability," *Orbis* 60, no. 2: pp. 188–203.

deploy nuclear weapons.[22] AI-enabled capabilities that increase the vulnerability of second-strike capabilities (or are perceived to do so) heighten uncertainty and undermine deterrence, even if the state in possession of these capabilities did not intend to use them. In short, the capabilities AI might enhance (cyber weapons, drones, precision-strike missiles, and hypersonic weapons), together with the ones it might enable (intelligence, surveillance and reconnaissance, machine-learning automatic target recognition, and autonomous sensor platforms), could make hunting for mobile nuclear arsenals faster, cheaper, and more effective than before.

AI-enabled Cyber Threats to Nuclear Command-and-Control

Today, it is thought possible that a cyberattack (e.g., spoofing, hacking, manipulation, and digital jamming) could infiltrate a nuclear weapons system, threaten the integrity of its communications, and ultimately (and possibly unbeknown to its target) gain control of its — possibly dual-use — command-and-control systems. For instance, a non-state third-party hacker might interfere with or sabotage nuclear command-and-control systems, spoof or otherwise compromise early warning systems (or components of the nuclear firing chain), or in a worst-case scenario, trigger an accidental nuclear launch.[23]

Advances in AI could also exacerbate this cybersecurity challenge by enabling improvements to the cyber offense. AI-augmented cyber tools' machine speed could enable an attacker to exploit a narrow window of opportunity to penetrate an adversary's cyber defences or use APT (advanced persistent threat) tools to find new vulnerabilities faster and easier than before.[24]

AI-enabled Drone Swarming and Nuclear Risk

Drones (especially micro-drones) used in swarms are conceptually well suited to conduct pre-emptive attacks and nuclear ISR missions against an adversary's nuclear mobile missile launchers, ballistic missile submarines, and their enabling facilities (e.g., early-warning systems, antennas, sensors, and air intakes). In short, the ability of drone swarming technology infused with future iterations of AI and machine learning — mining expanded and dispersed data pools — to locate, track, and target strategic missiles (e.g., mobile ICBM launchers in underground silos and on-board stealth aircraft or submarines) is set to grow.

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22 Lieber, K.A., & Press, D.G., (2013), "Why States Won't Give Nuclear Weapons to Terrorists," *International Security* 38, no. 1: pp. 80–104.
23 Johnson, J., (2021). "'Catalytic Nuclear War' in the Age of Artificial Intelligence & Autonomy: Emerging Military Technology and Escalation Risk between Nuclear-Armed States," *Journal of Strategic Studies*. **Link:** https://doi.org/10.1080/01402390.2020.1867541.
24 Johnson, J., (2019). "The AI-Cyber Nexus: Implications for Military Escalation, Deterrence, and Strategic Stability," *Journal of Cyber Policy* 4, no. 3: pp. 442–460.

Notwithstanding the remaining technical challenges — especially the demand for power — swarms of robotic systems fused with AI and machine-learning techniques may presage a powerful interplay of increased range, accuracy, mass, coordination, intelligence, and speed in a future conflict.

Automating Strategic Decisions with AI and Nuclear Risk

On the one hand, future AI-augmented command-and-control support tools may overcome many of the shortcomings inherent to human strategic decision making during wartime (e.g., susceptibility to invest in sunk costs, skewed risk judgement, heuristics, and groupthink) with potentially stabilising effects.[25] Further, faster and more reliable AI applications could also enable commanders to take decisions that are more informed during a crisis, improve the safety and reliability of nuclear support systems, strengthen the cyber defences of command-and-control networks, enhance battlefield situational awareness, and reduce the risk of human error caused by fatigue and repetitive tasks.[26]

On the other hand, AI systems that allow commanders to predict the potential production, commissioning, deployment, and ultimately launch of nuclear weapons by adversaries will likely lead to unpredictable system behaviour and outcomes, which *in extremis* could undermine first-strike stability — the premise of mutually assured destruction — making nuclear wars appear 'winnable'.[27]

AI and escalation control

However, the effect of AI at a strategic level remains uncertain. AI systems that are programmed to pursue tactical and operational advantages aggressively, for example, might misperceive (or ignore) an adversary's signal to resolve (i.e., to de-escalate a situation) as a prelude to an imminent attack. These dynamics would increase the risks of inadvertent escalation and incentives to use nuclear weapons first in a conflict.

If commanders decide to delegate greater authority to inherently inflexible AI systems, the dehumanisation of future defence planning will undermine stability by significantly inhibiting induction. Human induction — the ability to form general rules from specific pieces of information — is a crucial aspect of defence planning, primarily to manage situations that require high levels of visual and moral judgement and reasoning.

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25 Johnson, J., (2020), "Delegating Strategic Decision-Making to Machines: Dr. Strangelove Redux?" *Journal of Strategic Studies*. **Link:** doi: 10.1080/01402390.2020.1759038.

26 Hersman, R. et al., (2020). "Under the Nuclear Shadow: Situational Awareness Technology and Crisis Decision-making," *Center for Strategic and International Studies*, March 18, https://ontheradar.csis.org/analysis/final-report/.

27 Lieber, K.A., and Press, D.G., (2006). "The End of MAD: The Nuclear Dimension of US Primacy," *International Security* 30, no. 4 (Spring): pp. 7–44.

Unwarranted confidence in and reliance on machines — known as "automation bias" — in the pre-delegation of the use of force during a crisis or conflict, let alone during nuclear brinksmanship, might inadvertently compromise states' ability to control escalation.

Perceptions of AI's deterrent effect

Under crisis and conflict conditions, AI's deterrent effect is predicated on the perceived risks associated with a particular capability it enables or enhances. With higher uncertainty, deploying AI-augmented capabilities in a crisis might encourage an adversary to act more cautiously and, in turn, bolster stability. Counterintuitively, therefore, states may view the expanded automation of their nuclear command-and-control systems as a way to manage escalation and strengthen deterrence, signalling to an adversary that any attack — or the threat of one — might trigger nuclear escalation.

Because of the difficulty of demonstrating a posture like this *before* a crisis or conflict, this implicit threat — akin to the Dr Strangelove doomsday machine farce (or parable) — may equally worsen crisis instability. Moreover, the confusion and uncertainty that would result from mixing various (and potentially unknown) levels of human-machine interactions, along with AI reacting to events — such as signalling and low-level conflict — in nonhuman ways (using force where a human commander would not have) and at machine speed, could dramatically increase inadvertent risk.

Non-Nuclear Operations

AI could also be used to enhance a range of conventional capabilities related to nuclear war fighting in a number of ways, especially strategic non-nuclear weapons used in conventional counterforce operations.[28]

AI and penetration of enemy defences

Machine learning could increase the on-board intelligence of manned and unmanned fighter aircrafts, thus increasing their capacity to penetrate enemy defences using conventional high-precision munitions. Moreover, increased levels of AI-enabled autonomy might allow unmanned drones — possibly in swarms — to operate in environments hitherto considered inaccessible or too dangerous for manned systems (e.g., anti-access and area denial zones, or deep-water and outer space environments). The 2021 Azerbaijani-Armenian war and the recent Russian-Ukrainian war have demonstrated

28 Futter, A. & Zala, B., (2021). "Strategic Non-Nuclear Weapons and the Onset of a Third Nuclear Age," *European Journal of International Security* 6, no. 3: pp. 1–21.

how smaller states can integrate new weapon systems to amplify their battlefield effectiveness and lethality.[29]

AI and strategic defensive systems

Machine-learning techniques could materially enhance missile, air, and space defence systems' ability to detect, track, target, and intercept. Though AI technology has been integrated with automatic target recognition to support defence systems since the 1970s, the speed of defence systems' target-identification — because of the limited database of target signatures that an automatic target recognition system uses to recognize its target — has progressed slowly. Advances in AI and particularly generative adversarial networks could alleviate this technical bottleneck, generating realistic synthetic data to train and test automatic target recognition systems.[30] Besides, autonomous drone swarms might also be used defensively (e.g., decoys or flying mines) to buttress traditional air defences.

AI and cyber

AI technology is also changing how (both offensive and defensive) cyber capabilities are designed and operated. On the one hand, AI might reduce a military's vulnerability to cyberattacks and electronic warfare operations.[31] On the other hand, advances in AI machine learning (notably an increase in the speed, stealth, and anonymity of cyber warfare) might enable identifying an adversary's "zero-day vulnerabilities" — that is, undetected or unaddressed software vulnerabilities. Motivated adversaries might also use malware to take control, manipulate, or fool the behaviour and pattern recognition systems of autonomous systems.

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29 See Shaikh, S. & Rumbaugh, W., (2020). "The Air and Missile War in Nagorno-Karabakh: Lessons for the Future of Strike and Defense," *CSIS*, December 8, https://www.csis.org/analysis/air-and-missile-war-nagorno-karabakh-lessons-future-strike-and-defense; Burgess, M., (2022). "Small Drones Are Giving Ukraine an Unprecedented Edge From surveillance to search-and-rescue, consumer drones are having a huge impact on the country's defense against Russia," *Wired*, 5 June, https://www.wired.co.uk/article/drones-russia-ukraine-war

30 Stanton, G. & Irissappane, A.A., (2019). "GANs for Semi-Supervised Opinion Spam Detection," arXiv (March 19), arXiv, http://arxiv.org/abs/1903.08289; and Aghakhani, H. et al., (2018). "Detecting Deceptive Reviews Using Generative Adversarial Networks," arXiv (May 25), arXiv, http://arxiv.org/abs/1805.10364.

31 US Defense Advanced Research Projects Agency, "New DARPA Grand Challenge to Focus on Spectrum Collaboration," *DARPA*, March 23, 2016, https://www.darpa.mil/news-events/2016-03-23.

Summary

Because of the potentially transformative effects of AI and autonomy augmentation on a range of (nuclear and non-nuclear) strategic technologies, we need to urgently rethink existing assumptions, theories, and permutations of deterrence, premised on perceptions, nuanced signalling, and human rationality on both sides to ensure threats will suffice to shape the behaviour of others.[32] To make matters worse, AI algorithms to power (semi)autonomous systems today are based on game and decision-theoretic "rational" decision-making — to predict an adversary's intentions and behaviour more accurately in simulated battlefield situations.

Replacing human agency and rationality with "black box" algorithms, the technology might obscure and erode established deterrence mechanisms, norms, and policies.[33] Will planners become too reliant on AI technology, believing it to be imbued with superhuman intelligence, or distrust its recommendations because of AI's non-human "black box" fuzzy logic? To be sure, in human-machine interactions trust in automation and algorithmic systems includes not only factors related to performance but also those necessary for individuals to interact with them — such as the purpose and goals of algorithms, and the personality, cultural traits, and intentions of human operators.[34]

Notwithstanding the possible reduced risk to human life, the total absence of a normative deterrence framework — particularly to signal resolving to an adversary while simultaneously seeking to de-escalate a situation — is troublesome.[35] In sum, an over-reliance on AI to inform strategic decisions by demoting the role of human agents in reviewing, scrutinising, and invalidating the assumptions about an adversary's intentions and behaviour (critical to effective deterrence) increases the risk of inadvertent escalation. That is, complicating the delicate balance between an actor's willingness to escalate a situation as a last resort and keeping the option open to step back from the brink.

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32 See Fearon, J., (1995). "Rationalist Explanations for War," International Organization 49, no. 3: pp. 379–414; and Thayer, B.A., (2007). "Thinking about Nuclear Deterrence Theory: Why Evolutionary Psychology Undermines Its Rational Actor Assumptions," *Comparative Strategy* 26, no. 4: pp. 311–323.

33 See Vrancx, P., Nowe, A., and De Hauwere, Y. (eds), (2012) *Reinforcement Learning: Adaptation, Learning, and Optimization* (Berlin: Springer), pp. 441–470.

34 See Aroyo, A. et al., (2021), "Overtrusting Robots: Setting a Research Agenda to Mitigate Overtrust in Automation," *Journal of Behavioral Robotics* 12, no. 1: pp. 423–443.

35 Johnson, J., (2022). "Inadvertent Escalation in the Age of Intelligence Machines: A New Model for Nuclear Risk in the Digital Age," *European Journal of International Security*, 7, no. 3: pp. 337–359.

LUCK,
CLOSE-CALLS
AND ENTANGLEMENT

1.3 Luck, close-calls and entanglement

There is a well-established scholarship on nuclear weapons accidents and close calls, including in nuclear crises, notably the 1962 Cuban Missile Crisis.[1] New scholarship using new sources and new cases continues to be produced. This briefing highlights new scholarship published over the course of the humanitarian initiative on nuclear weapons on nuclear near-misses, luck and how the potential for further near-misses is being compounded by the 'entanglement' of nuclear and conventional weapon systems.

Luck and close calls

Sokolski, H. & Tertrais, B. (Eds.), (2013). *Nuclear Weapons Security Crises? What Does History Teach Us?* (U.S. Army War College Press: Carlisle, PA).
Link: https://npolicy.org/nuclear-weapons-security-crises-what-does-history-teach/

This edited volume builds on existing work to show that security practices for nuclear weapons have often been insufficient and lax with the authority to use nuclear weapons often pre-delegated to commanders in the field or at sea. The collection of authors uses new evidence to highlight the risk of severe political upheavals in nuclear-armed states, including coups d'état, that affected the security of nuclear weapons and/or control of use in one way or another. The cases are in China (1966 Cultural Revolution and Second Artillery Corps), Russia (1990 Azerbaijan uprising; 1991 coup; 1993 attempted coup), France (1961 coup in Algiers) and Pakistan (history of civil-military political transitions and coups).

The research shows that the history of nuclear security and control is fraught with lax procedures and insufficient measures compounded by human mistakes. It demonstrates the degree to which even sophisticated command-and-control systems are vulnerable to failure in times of political instability and that the loss of checks and balances in a nuclear weapons command-and-control system increases the likelihood of unauthorised use.

Peter Feaver's chapter in particular draws on the four cases to show that leaders worried and had reason to worry about the integrity of their command-and-control system during periods of political turmoil, and that ad hoc fixes introduced to address these concerns led to new problems. It further clarifies that unplanned political transitions can increase the risk that nuclear security and safety will be compromised and some degree of loss

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1 For a good summary see Lewis, P., Williams, H., Pelopidas, B. & Aghlani, S., (2014). *Too Close for Comfort Cases of Near Nuclear Use and Options for Policy*, Chatham House. **Link:** https://www.chathamhouse.org/2014/04/too-close-comfort-cases-near-nuclear-use-and-options-policy

of at least some crucial aspects of nuclear command and control has actually happened, for example, in the Ukraine crisis in 1991, and that control over nuclear weapons can become a totem of power that new political authorities found irresistible. Lastly, Feaver's chapter explains that the military's professionalism is partly a function of the fiscal health of the institution such that command and control by under-resourced militaries can be compromised in periods of political instability.

Pelopidas, B., (2022). *Repenser Les Choix Nucleaires/Rethinking Nuclear Weapons Choices* (Paris: Science-Po Press).

Pelopidas is the first scholar to provide a systematic study of luck and nuclear weapons complexes. He shows that "Poor practices in nuclear weapons management have occurred at all levels of decision-making in the past, are still happening today and are likely to continue in the future." His research demonstrates the role of luck in preventing nuclear use and shows at the same time how supporters of nuclear deterrence deny the role of luck. Here, luck is different to risk. Risk implies an uncertainty that can be known, managed and even manipulated for political gain. Luck refers to an unknowable uncertainty.

Pelopidas uses case studies of real-world events to demonstrate how luck or chance, has prevented nuclear detonations in three ways:

1. Lucky cases are those where things went wrong such that a nuclear weapon should have detonated, and only luck can explain why it did not do so.
2. Lucky cases are those where following standard control practices would have led (or likely led) to a nuclear detonation, and the reason control practices were not followed can only be explained by luck, for example chance insubordination.
3. Lucky cases are those outside the remit of control practices a nuclear weapon did not detonate because of random chance. For example, the role of the wind during the fire at Grand Forks Air Base in the US in 1980 that blew a fire that started when a B-52 engine exploded away from the B-52s on the runway armed with tactical nuclear missiles. (see also Schlosser, Command and Control, p.381 and 384).

Moreover, Pelopidas shows the ways in which the role of luck is made invisible in analysis of nuclear weapons policy, especially by supporters of nuclear deterrence, in order to sustain a paradigm of nuclear control.

Schlosser, E. (2013). *Command and Control: Nuclear Weapons, the Damascus Accident and the Illusion of Safety* (Penguin: New York).

Schlosser provides a ground-breaking account of nuclear weapons accidents, near-misses, and luck in avoiding inadvertent nuclear disaster. He documents in detail the 'Damascus accident' in 1980 when a US Titan ICBM at Missile Complex 374-7 near Damascus, Arkansas, exploded. A series of errors and accidents caused the missile's liquid fuel to explode when a dropped socket ruptured the stage one fuel tank. Part of the missile flew high out of the silo and smashed to earth with its nine-megaton warhead. The warhead's re-entry vehicle was destroyed, but otherwise the warhead was largely intact. In telling the story, Schlosser provides details of many more accidents involving US nuclear weapons and the bureaucratic challenges of prioritising warhead safety in the US nuclear weapons complex over the course of the Cold War. The detailed cases and human stories demonstrate the fallibility of nuclear weapons control systems and the people and organisations that operate them.

Sherwin, M. (2020). *Gambling with Armageddon: Nuclear Roulette from Hiroshima to the Cuban Missile Crisis* (New York: Knopf) and Plokhy, S. (2021). *Nuclear Folly: A History of the Cuban Missile Crisis* (New York: Norton).

Both Sherwin and Plokhy present new findings on the Cuban Missile Crisis using new sources. Sherwin shows in his study of the Cuban Missile Crisis and its wider context that history demonstrates the disadvantages of nuclear weapons outweigh their advantages. Pulitzer Prize–winning Sherwin, who was a preeminent historian of the missile crisis and the development of atomic energy, demonstrates the extent to which luck played a vital role in avoiding escalation to nuclear war in this crisis. Plokhy examines the many mistakes during the crisis by political leaders in the US, Soviet Union and Cuba using newly declassified Russian sources. He unpacks the extent of poor decision-making, inadequate intelligence gathering, misunderstanding, and ideological hubris to show that Kennedy and Khrushchev "marched from one mistake to another". Plokhy's analysis further undermines the dominant narrative of US historians that claims the condition of 'mutually assured destruction' ensured a peaceful outcome. He also shows with new evidence that avoiding nuclear war depended on good luck.

Radchenko, R. & Zubok, V. (2023). Blundering on the Brink: Secret History and Unlearned Lessons of the Cuban Missile Crisis. *Foreign Affairs*, April 3. Link: https://www.foreignaffairs.com/cuba/missile-crisis-secret-history-soviet-union-russia-ukraine-lessons

The authors use newly available Russian Ministry of Defence archives opened in May 2022 that "shed new light on the most hair-raising of Cold War crises, challenging many assumptions about what motivated the Soviets' massive operation in Cuba and why it failed so spectacularly". They show that Khrushchev's decision to send missiles to Cuba was a poorly thought-through gamble whose success depended on improbably good luck and was plagued by a total lack of understanding of conditions in Cuba. Secretive and hasty planning for the operation in Moscow led to many mishaps, poor decision-making and wholly inadequate planning for the missile deployments in Cuba itself. They reinforce the conclusion that Khrushchev embarked on a reckless gamble using new archival evidence.

Kaplan, F. (2020). *The Bomb: Presidents, Generals, and the Secret History of Nuclear War* (New York: Simon & Schuster) and Ellsberg, D. (2017). *The Doomsday Machine: confessions of a nuclear war planner* (New York, Bloomsbury).

Two books published by Kaplan and Ellsberg (of The Pentagon Papers fame) demonstrate in detail how US presidents over the history of the nuclear age tried and failed to adjust US nuclear strategy to enable limited nuclear attack options rather than a semi-automated massive attack. Kaplan, Ellsberg and Schlosser show that nuclear weapons acquisition was driven by inter-service rivalry and organisational budgets and that nuclear war planners in the US military made no serious attempt to understand the full humanitarian and environmental impact of their war plans and made no attempt in those plans to limit civilian casualties. Both Ellsberg and Schlosser detail the very many problems with US nuclear weapons command and control and safety during the first decades of the Cold War, the very real risk of inadvertent nuclear detonations and potentially nuclear war, and the embedding of the 'The Bomb' in an organisational and cultural nuclear 'Doomsday Machine' that continues to threaten catastrophe.

Entanglement

A key change in the global politics of nuclear weapons is the complexity of the global security environment. This affects our understanding of the risk of nuclear violence in two important ways: first, in terms of the complexities introduced by new technologies; and second, in terms of the cascading effects of nuclear detonations (see briefing 1.5). A number of studies have examined the risks of growing 'entanglement' of conventional and nuclear weapon and support systems, especially command-and-control systems.

Acton, J. (2018). Escalation through Entanglement: How the Vulnerability of Command-and-Control Systems Raises the Risks of an Inadvertent Nuclear War. *International Security*. 43: 1, 56–99. Link: https://doi.org/10.1162/isec_a_00320

Acton argues that the risks of inadvertent escalation are even more serious than often accepted and are likely to increase significantly in the future. This is because Chinese, Russian, or US command, control, communication and intelligence (C3I) assets located outside a theatre of operation could be attacked over the course of a conventional conflict. These assets include satellites used for early warning, communication, and intelligence, surveillance, and reconnaissance (ISR); ground-based radars and transmitters; and communication aircraft. These assets are central to these states' nuclear command-and-control systems, but they are also 'entangled' with non-nuclear weapons that would be used in a conventional conflict in two ways. First, they are typically dual-use because they enable both nuclear and non-nuclear operations. Second, they are increasingly vulnerable to non-nuclear attack.

The danger is that in a US-Chinese or US-Russian conflict, both sides could have strong incentives to attack the adversary's dual-use C3I capabilities to undermine its non-nuclear operations. As a result, over the course of a conventional war, the nuclear C3I systems of one or both of the belligerents could become severely degraded. This could incentivise escalation if such attacks are interpreted as a prelude to a nuclear attack. The analysis shows that the US, China and Russia are all improving their capabilities to threaten potential adversaries' C3I assets and that the extent of entanglement — and hence the magnitude of these escalation risks — is likely to increase.

Acton, J. (2020). Cyber Warfare & Inadvertent Escalation. *Daedalus*. 149: 2, 133–49.
Link: https://www.jstor.org/stable/48591317

Acton goes on to show that nuclear C3I is increasingly vulnerable to cyber espionage and attack. The particular area for concern is inadvertent cyber threats against, or interference with one state's nuclear forces or C3I systems by another nuclear-armed state. He argues that because of their unique characteristics and effects, cyber threats could create at least three qualitatively new mechanisms by which a nuclear-armed state might come to the incorrect conclusion that its nuclear deterrent was under threat: purpose of cyber interference could be misinterpreted; a cyberattack could have a more significant effect than intended; and the initiator of a cyber operation could be misidentified. He notes that cyber weapons offer an unparalleled capability to manipulate the data that go into nuclear C3I decision-making. Cyber weapons represent a sea change because their effects can be tailored with great precision in real time, and because they could be used to directly influence the perceptions of high-level decision-makers. In this context, Chinese and Russian fears that the US is seeking the capabilities–non-nuclear capabilities, in particular–to negate their nuclear deterrents could prove escalatory in a crisis or conflict by generating 'crisis instability', that is, pressures to use nuclear weapons before losing the capability to do so.

Gartzke, G. & Lindsay, J. (2017). Thermonuclear cyberwar. *Journal of Cybersecurity*. 3: 1, 37-48. **Link:** https://doi.org/10.1093/cybsec/tyw017

Gartzke and Lindsay also explore pathways to escalation in a conventional US-China conflict. They also argue that conventional military strikes in conjunction with cyberattacks that blind sensors and confuse decision-making could generate incentives for both sides to rush to pre-empt or escalate a conflict. This is especially true if nuclear command, control, and communications systems are subjected to cyberattack. The authors describe nuclear C3I as

> "the nervous system of the nuclear enterprise spanning intelligence and early warning sensors located in orbit and on Earth, fixed and mobile command and control centres through which national leadership can order a launch, operational nuclear forces including

> strategic bombers, land-based intercontinental missiles (ICBMs), submarine-launched ballistic missiles (SLBMs), and the communication and transportation networks that tie the whole apparatus together".

They highlight a series of official US reports that demonstrate serious concerns about the vulnerability of the nuclear C3I system. They show that it is the temptation to disrupt nuclear C3I *in case* deterrence breaks down that can increase the risk of deterrence actually breaking down.

Hersman, R., Younis, R., Farabaugh, B., Goldblum, B., & Reddie, A. (2020). ***Under the Nuclear Shadow: Situational Awareness Technology and Crisis Decisionmaking,*** **CSIS, Washington, D.C.. Link:** https://www.csis.org/analysis/under-nuclear-shadow-situational-awareness-technology-and-crisis-decisionmaking

Hersman et al examine the growing complexity of the US situational awareness architecture that gathers and processes data in order to understand the operating environment for military forces, detect nuclear and conventional strategic attacks, and discern real attacks from false alarms. They argue that from around 1950 to 1990 nuclear and conventional situational awareness systems were largely isolated from each other and operated independently. Over the first three decades of the post-Cold War period from 1990 to 2020, the nuclear and conventional situational awareness ecosystems began to blur together driven by technological innovation and the desire for unequalled information dominance and precision warfare. Since 2020, the emerging situational awareness ecosystem is highly networked, operates in real-time, and is dual use. This has created a highly capable situational awareness ecosystem, but one that is more complex and prone to new types of escalation risk.

Systems for US nuclear command, control and communications are now almost all dual use: systems previously used for nuclear situational awareness now support conventional operations and systems developed for conventional situational awareness now also support nuclear operations. This generates risks of escalation through the targeting of an adversary's situational awareness systems in a conventional conflict that *also* undermines the viability of the adversary's *nuclear* forces. This could generate incentives to use *nuclear* weapons based on the risk of losing the ability to use them as a conflict escalates and situational awareness deteriorates. These risks can lead decision-makers to believe either that their own nuclear forces are vulnerable to a disarming strike or that there is an opportunity to disarm an adversary.

Moreover, the emerging situational awareness ecosystem creates information complexity based on vast amounts of information that has to be processed and presented perhaps rapidly in ways that are useful to decision-makers. Decision-makers' inability to seek, manage, and interpret information effectively can result in decisional paralysis or biased decision-making, which can impair effective crisis management. In the national security field, it is widely assumed that more and better information, provided more quickly, leads to more decision time and therefore better decision-making. However, this may not always be the case. In a complex information environment where data may be neither easily understood nor highly trusted and relies on unfamiliar technologies, cognitive processes could increase both the risks and the stakes in crisis decision-making.

Durkalec, J., Peczeli, B. & Radzinsky, B. (2022). Nuclear decisionmaking, complexity and emerging and disruptive technologies: A comprehensive assessment. Lawrence Livermore National Laboratory. Link: https://www.osti.gov/servlets/purl/1843557

The authors argue that major military powers and their allies are currently racing to develop and incorporate 'emerging and disruptive technologies' into weapons systems, strategy and doctrine to realise military advantages. These 'EDTs' include artificial intelligence and big data analytics, AI-enabled cyber operations, cheaper and smarter space assets and space weapons, autonomous systems, hypersonic weapons, and quantum technology.

The technologies will intersect with each other and nuclear weapons in novel ways that *could* significantly impact nuclear decision-making, particularly in an escalating regional conventional conflict. This presents a range of opportunities for managing nuclear crises and risks of crisis escalation. The authors argue that every hypothesis about the disruptive effects of EDTs and multi-domain complexity generates a counter-hypothesis because the complex interactions of EDTs could positively or negatively impact both the context in which nuclear decisions are taken and the choices made. Some combinations of EDTs could improve the decision-maker's ability to make a more informed decision during a rapidly escalating crisis or conflict, but in other circumstances combinations of EDTs could generate overconfidence in a decision-maker, decision paralysis, or mistrust in information and analysis.

Fully understanding the impact of these technologies is difficult because of the complexity associated with the combined use of EDTs. There are a number of fundamental aspects of this complexity. Nuclear powers armed with EDTs will face other nuclear powers armed with their own technologies. How each side acts will depend not only on its own capabilities and objectives but on those of the other side. This interactive process will likely involve various degrees of human-human, human-machine, and machine-machine interaction as decision-makers attempt to act strategically while contending with their own technological systems and the interaction of their systems with the adversary's technological systems. All these interactions will take place in an uncertain environment that is obscured by the 'fog of war'.

Bracken, P. (2020). Communication Disruption Attacks on NC3. NAPSNet Special Reports. Link: https://nautilus.org/napsnet/napsnet-special-reports/communication-disruption-attacks-on-nc3/

Bracken argues that attacking enemy communications leads to greater risks of uncontrolled escalation in conflicts between nuclear-armed states. He shows that in the 1980s it became clear that the US communications systems was the weak link in the nuclear posture. Bracken examines the breakdown of the US communication system on 11 September 2001 when Al Qaida attacked the World Trade Center and the Pentagon. 'Continuity of government' plans for protecting US leadership and ensuring that it had communication links to the military utterly failed to be implemented because the officials involved either didn't know what it was or did not follow their assignments in the chaos of the situation. Bracken shows that a small, unanticipated attack paralysed elements of the command system. The attack wasn't even intended to do this, yet it did.

In what Bracken calls "yet another example that truth is stranger than fiction", the 9/11 attacks coincided with an unrelated, long-planned nuclear war game exercise that involved uploading live warheads onto B-52 bombers at Barksdale Air Force Base. President George W. Bush was in Florida when the attacks took place. He was quickly evacuated on Air Force One, which then needed to refuel. Barksdale Air Force Base was the chosen destination. In response to the attacks the Pentagon wanted to raise the US alert level, but to do so they needed to secure the live bombs being used in the nuclear war game exercise, and this created a lot of problems. In particular, it required presidential approval at a time when the president was airborne, not in communication with the Pentagon, and set to land on an airfield full of dispersed hydrogen bombs. He says, "It is worth thinking about this for a moment because it shows a set of coincidences that were incredibly unlikely—and yet they happened". He shows that a review of Cold War nuclear-related accidents shows the same thing: the tendency for the real world to come up with scenarios that were far more creative and dangerous than any planner could think up. He makes the point that "If the scenario that did occur on 9/11 was offered as a Hollywood script it would be rejected out of hand as implausible. Yet it happened."

He argues that advanced technologies like cyber, stealth, anti-satellite attacks, and AI induced deception have now made the relationship between conventional and nuclear weapons and command-and-control systems much more complicated and that "We do not understand this divide. It is not a good strategy to discover the contours of this divide in a real crisis or war."

PSYCHOLOGY AND NUCLEAR DECISION-MAKING

1.4 Psychology and nuclear decision-making

Beginning in the 1970s, a substantial body of research has investigated nuclear weapons decision-making processes using insights from psychology, social psychology, and organisation theory, but it peaked in the late 1980s. Some of this work has since continued over the period of the 'humanitarian initiative on nuclear weapons', generating new findings that build on the established scholarship. In particular, Paul Slovic, Professor of Psychology at the University of Oregon, together with a number of co-authors has looked at these issues in detail over the past decade.

Harrington, A & Knopf, J. (Eds.). (2019). *Behavioural Economics and Nuclear Weapons* (University of Georgia Press, Athens). Link: https://ugapress.org/book/9780820355634/behavioral-economics-and-nuclear-weapons/

This edited volume applies insights from behavioural economics to nuclear weapons decision-making. The editors note that research in psychology and neuroscience shows that people routinely deviate from standard social models of behaviour based on the 'rational actor model'. The idea of a universal form of rationality in which people make detached and objective calculations of costs and benefits is rejected. These insights form the basis of behavioural economics, which provides a more accurate basis for understanding how people think and why they act in the ways that they do. They find that: 1) understanding how actors subjectively frame nuclear issues, crises, and choices is essential since this has a huge impact on the choices people make; 2) emotions have a powerful effect on human decisions and behaviour in nuclear contexts; 3) people are motivated to minimise losses rather than maximise gains (in line with prospect theory); 4) people care about issues of justice and fairness when making choices, but generally in self-serving ways; 5) time horizons matter in decision-making, and longer time horizons allow for more deliberative reasoning.

Slovic, P., Mertz, C. K., Markowitz, D., Quist, A., & Västfjäll, D. (2020). Virtuous violence from the war room to death row. *Proceedings of the National Academy of Sciences*. 117: 34, 20474–20482.
Link: https://www.pnas.org/doi/pdf/10.1073/pnas.2001583117

Slovic et al examine public opinion surveys to understand whether public opinion in the United States would oppose or support a decision by the president to use nuclear weapons in an international crisis, including a crisis with Iran. In particular, they draw on and extend surveys by Scott Sagan and Benjamin Valentino.[1] Slovic's et al results show evidence of psychological processes of dehumanisation of Iranians, vengefulness and a belief that the use of nuclear weapons was ethical and that the victims were to blame for their fate, with Iranian leaders being morally responsible.

The authors also evidence the psychological process of 'psychic numbing' where people become insensitive to civilian death tolls as the numbers rise from one, to a few to thousands, which can explain public indifference to genocide. This shows that prejudicial social, cultural, and political attitudes drive policies and decisions that devalue and harm human lives, including decisions about using nuclear weapons. These psychological processes of numbing, dehumanisation and victim blaming enable mass murder to proceed without challenge from the type of feelings that would arise from harming human beings recognised as being similar to one's self.

They argue that public opinion surveys show that the US public is numb to the consequences of nuclear conflict and are ready to abandon the principle of non-combatant immunity under the pressures of war. These findings suggest that public opinion is unlikely to be a serious constraint on a US president contemplating the use of nuclear weapons in wartime.

They also show that political and ideological factors loom large, with Republicans, conservatives, and Trump voters more than three times more likely than Democrats, liberals, and Trump non-voters to approve the nuclear strike in the survey scenario.

They note that political leaders are comfortable, even proud, to make important military decisions according to their 'gut instinct', which will be guided by these psychological processes. They argue that their study raises questions about whether we can be assured that political ideologies and sociocultural biases, so prevalent among the public, do not also influence important military decisions.

Slovic, P. (2020). Risk Perception and Risk Analysis in a Hyperpartisan and Virtuously Violent World. *Risk Analysis.* 40: S1. Link: https://doi.org/10.1111/risa.13606

Slovic looks at how people understand risk in relation to how we value the saving of human lives. Research shows that we value saving small numbers of lives greatly, but this levels off as numbers increase and people become insensitive to additional increases.

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1 Press, D., Sagan, S. & Valentino, B. (2013). Atomic Aversion: Experimental Evidence on Taboos, Traditions, and the Non-Use of Nuclear Weapons. *The American Political Science Review.* 107: 1, 188–206. **Link:** http://www.jstor.org/stable/23357763. D. Sagan, S. & Valentino, B. (2017). Revisiting Hiroshima in Iran: What Americans Really Think about Using Nuclear Weapons and Killing Noncombatants. *International Security.* 42: 1, 41–79. **Link:** https://doi.org/10.1162/ISEC_a_00284.

This is supported by brain imaging studies that demonstrated that the core empathy network including the medial prefrontal cortex (mPFC) was more engaged for events happening to a single person than those happening to many people. These psychological phenomena are called 'numbing' and 'compassion fade'.

A third phenomenon called 'the prominence effect' further helps explain why even slow, reasoned decision-making can be severely biased. This phenomenon says that people often default to choosing the option that is better for the most prominent or defensible attribute. When it comes to saving lives, 'national security' routinely becomes the most prominent attribute, and this explains the repeated failure of powerful states, such as the United States, to intervene in humanitarian crises like genocides and mass atrocities, despite recognising a moral responsibility to act. This body of research shows that even strongly held humanitarian values tend to decline or even collapse when up against 'national security' objectives, no matter how many thousands or millions of lives hang in the balance. Moreover, Slovic shows that because attention is a limited resource, we tend to simplify complex trade-offs by focusing on prominent objectives and neglecting other objectives that are not as prominent.

Slovic et al. found support for using nuclear weapons to kill millions of enemy civilians in a hypothetical war to be tightly connected with support for other harmful domestic actions and policies. These were support for anti-abortion policies, the death penalty for serious crimes, anti-gun control, and harsh anti-immigration policies. They show that this set of attitudes is bound together by a desire to punish others who one judges to be bad and thus deserving to be dealt with harshly.

Slovic P., & Lin, H. (2020). The Caveman and the Bomb in the Digital Age. In H.A. Trinkunas, H.S. Lin, & B. Loehrke (Eds.) *Three tweets to midnight: Effects of the global information ecosystem on the risk of nuclear conflict* (Stanford, CA: Hoover Institute Press), pp. 39-62, Link: https://www.hoover.org/sites/default/files/research/docs/trinkunas_threetweetstomidnight_39-62_ch.3.pdf

Slovic and Lin demonstrate 'the singularity effect' that shows that people place very high value on saving a single life, but that as the numbers increase 'psychic numbing' begins to desensitise people and 'compassion fade' reduces the perceived value of protecting large numbers of lives. Such a reduction, if large enough, enables the planner and decision-maker to proceed to kill millions in a manner they believe to be consistent with the laws of war. Their research on nuclear weapons shows that psychic numbing and security prominence are even more strongly evident in acts of war than in passive indifference to genocide and other major threats to life.

The authors argue that mass killing in warfare is accompanied by intense emotions such as anger, hatred and vengeance. These are understood through a framing of "us versus them" that psychologists refer to as tribalism. Tribalism and dehumanisation also enable people to believe that victims deserve their fate. Effects of this belief can be compounded by the "just world" hypothesis, which states that people need to believe that the world is just and that therefore people get what they deserve.

Blaming the victims allows the perpetrator to act without guilt against victims seen as less than human, to believe that the victims are evil, and the killing that leaders have told them to do is morally proper. Tribalism, dehumanisation, and victim-blaming enable mass murder to proceed without challenge from normal feelings, i.e., feelings that would arise from human beings' being recognized as similar to one's self.

We cannot know in advance how psychic numbing, compassion fade, tribalism, and dehumanisation might distort the decision-making calculus and choices of leaders in a nuclear crisis or conflict. This demonstrates the risk that political ideologies and socio-cultural biases influence decisions on the use of nuclear weapons.

Trinkunas, H.A., Lin, H.S., & Loehrke, B. (2020). "What Can Be Done to Minimize the Effects of the Global Information Ecosystem on the Risk of Nuclear War?" (Chapter 10) in H.A. Trinkunas, H.S. Lin, & B. Loehrke (Eds.) *Three tweets to midnight: Effects of the global information ecosystem on the risk of nuclear conflict* (Stanford, CA: Hoover Institute Press). Link: https://www.hoover.org/sites/default/files/research/docs/trinkunas_threetweetstomidnight_193-214_ch.10.pdf

The authors examine nuclear weapons decision-making processes within the context of a global information ecosystem. The existence of such an ecosystem is a key feature of the new context within which nuclear weapons must be reconsidered. The research shows that the new global communications ecosystem produces new opportunities to influence the public and decision-makers by playing on traditional cognitive biases we use to process information. Audiences, which can include senior policy-makers, can be more susceptible to effects on cognitive biases in crisis situations characterised by time pressure, high volumes of information, and false but plausible 'post-truth' narratives that find widespread public support. In particular, it has become much easier to produce polarisation in target populations, create waves of public opinion to influence enemy leaders, and conduct influence operations designed to target the psychology of enemy publics using masses of unverified information produced at high speed and distributed at high volume for next to no cost. The authors argue these trends call into question whether traditional models of crisis stability, which assume rational decisions made by elites based on the best available evidence, are an accurate way to understand the likely evolution of future international conflicts.

McDermott R. & Pauly, R. (2023). The Psychology of Nuclear Brinkmanship. *International Security.* 47: 3, 9–51. Link: https://doi.org/10.1162/isec_a_00451

The authors show that human emotions can introduce a degree of chance into conflicts between nuclear-armed states in ways that contradict the expectations of rational cost-benefit assumptions that underpin deterrence theory. They argue that there is nothing automatic about decision-making in a nuclear crisis, and that leaders still have choices to make. Because of this, psychological and emotional effects on decision-making are sources of risk, uncertainty, and ambiguity. They argue that these factors can make an already uncertain situation even more unstable and unpredictable.

They draw on scholarship on emotion to show that leaders in a nuclear crisis could become swept away by emotions such as anger or fear and take actions that they had not planned at the outset, especially under stress or in the face of loss. In times of stress and crisis, one of the most destabilising of these pressures is the desire for vengeance in the face of an attack. These factors can make an already uncertain situation even more unstable and unpredictable. The authors argue that there are many psychological and emotional reasons to believe that choosing to use force might not be rational in a particular crisis, and yet it is employed nonetheless in service of a leader's own bias, status, or ego. This is because chance and choice and decision-making itself in crises are as much psychological and emotional as rational processes.

They outline two well-established psychological biases that affect crisis decision-making. First, the 'illusion of control' whereby a leader overestimates their own control over events and outcomes and is overconfident in ways that risk expanding the conflict. Illusions of control can result in illusory pattern recognition, i.e. perceiving patterns that do not exist, including exaggerating the prospect that others will actually submit to threats and violence. Second, leaders tend to overestimate the adversary's unity and control. They see others' behaviours as more centralised, disciplined, and coordinated than they actually may be.

Within this lies the possibility of losing self-control where a leader chooses to escalate out of panic or madness, or from false alarms and the misapprehension of enemy intentions. Most leaders control their emotions most of the time, and some people certainly have greater emotional awareness, interpersonal skills or cognitive intelligence to read a crisis and diffuse it. But many people are not able to completely or consistently control their feelings. They fail to consider others' goals, perceptions, and capabilities, and refuse to accept the possibility that things may not go as planned. Deficits in emotional self-awareness and control result in the inability to make choices consistent with best interests.

Moreover, the authors show that different emotions trigger different perceptions of risk. For example, anger makes people more risk-seeking, and thus more likely to downplay the nature of the risks that they confront. It also makes them much more likely to believe that they will be victorious in a conflict, even if such a belief rests on pure overconfidence.

Conversely, fearful people have more pessimistic risk assessments and thus prove more risk averse in their choices and behaviours.

Finally, gender differences emerge in these tendencies as well. For example, men are more prone to anger, which predicts more support for punitive political policies. In contrast, some studies find that women tend to be more fearful and are thus much more likely to support rehabilitative policies.

McDermott, R., Lopez, A. & Hatemi, P. (2017). 'Blunt Not the Heart, Enrage It': The Psychology of Revenge and Deterrence. *Texas National Security Review.* 1: 1.
Link: http://hdl.handle.net/2152/63934.

The authors draw on recent work in psychology and behavioural primate studies to set out an evolutionary account of nuclear deterrence rooted in the psychology of revenge, or 'retaliatory aggression'. They argue that the well-studied psycho-physiological desire for revenge explains why policy-makers can sometimes readily commit to otherwise apparently 'irrational' retaliation, such as a nuclear attack even after catastrophic defeat and death are assured. This can have a deterrent effect because people, they argue, automatically and universally recognise the plausibility of nuclear vengeance. But this evolutionary behavioural explanation also overrides rationalist arguments about how nuclear deterrence is supposed to work. Here, "in the face of existential threat, revenge overwhelms the cost-benefit calculations that would otherwise lead rational actors to accept sunk costs and, instead, to return spiteful destruction on the attacker."

Wheeler, N. (2018). Trusting enemies: interpersonal relationships in international conflict (Oxford: Oxford University Press). Link: https://global.oup.com/academic/product/trusting-enemies-9780199696475?cc=gb&lang=en&

Nick Wheeler examines not how nuclear weapons decisions are made, but how the risk of nuclear conflict can be reduced through trust-building processes. Drawing on social psychology, this is the first body of research to systematically engage with the concept of trust and the process of trust building between nuclear-armed enemies. This builds on Wheeler's work with Ken Booth on the security dilemma, cooperation and nuclear crises. Wheeler argues that building trust at the interpersonal level of adversarial state leaders is both essential to diffusing tensions and resolving international conflicts and possible. Wheeler explains how signalling trust can be very difficult and shows ways in which this can be overcome. The key is to build 'bonding trust' through face-to-face meetings that enable steps towards positive rather than negative identification. The analysis is based on detailed historical case studies of trust-building meetings between President Ronald Reagan and Mikhail Gorbachev, Indian Prime Minister Atal Bihari Vajpayee and Pakistani Prime Minister Nawaz Sharif, as well as a failed process of trust building between President Barack Obama and Iran's Supreme Leader Ali Khamenei.

GLOBAL CATASTROPHIC RISK AND CASCADING COLLAPSE

1.5 Global catastrophic risk and cascading collapse

Over the past 20 years, the risk of omnicidal nuclear war has become part of the emerging field of 'global catastrophic risk'.[1] This research demonstrates that multiple nuclear detonations in a violent conflict are likely to have cascading effects across multiple global systems that are difficult to accurately predict in advance.

Scholarship on 'global catastrophic risk', 'existential risk' and 'planetary boundaries' driven in no small part by the global ecological crisis has fundamentally changed the context in which nuclear violence is understood. Risks can be categorised as 'global catastrophic risks' that could kill at least 1 billion people or around 10% of the population, 'civilisational collapse risks' based on a drastic reduction in human population, the break-down of connections between surviving populations, and the loss of technological abilities and knowledge, and 'human extinction risks' in which all humans die, and no future generations will ever exist.[2]

Research findings have demonstrated that the interconnectedness and complexity of global systems is now a core feature of world politics. Global systems are now highly interconnected, or 'tightly-coupled' in ways that generate potential for cascading effects. The concept of cascading disasters refers to a series of events that unfold in a sequential or interconnected manner, where the occurrence of one disaster triggers subsequent disasters, resulting in an amplification of the overall impact. These cascading effects can occur across various domains, such as environmental, economic, social, and technological. For example, a global pandemic can disrupt critical infrastructure, trigger economic collapse, and lead to social unrest, ultimately exacerbating the initial risk and causing further harm.

Research has shown how cascading disasters can trigger feedback loops, where the impacts of one event exacerbate the likelihood or intensity of subsequent events. For example, extreme weather events caused by global heating like hurricanes can intensify due to warmer ocean temperatures, leading to increased flooding and destruction. These disasters then further strain infrastructure, compromise ecological systems, cause population displacement, and create socio-economic vulnerabilities that can lead to or exacerbate the next set of crises.

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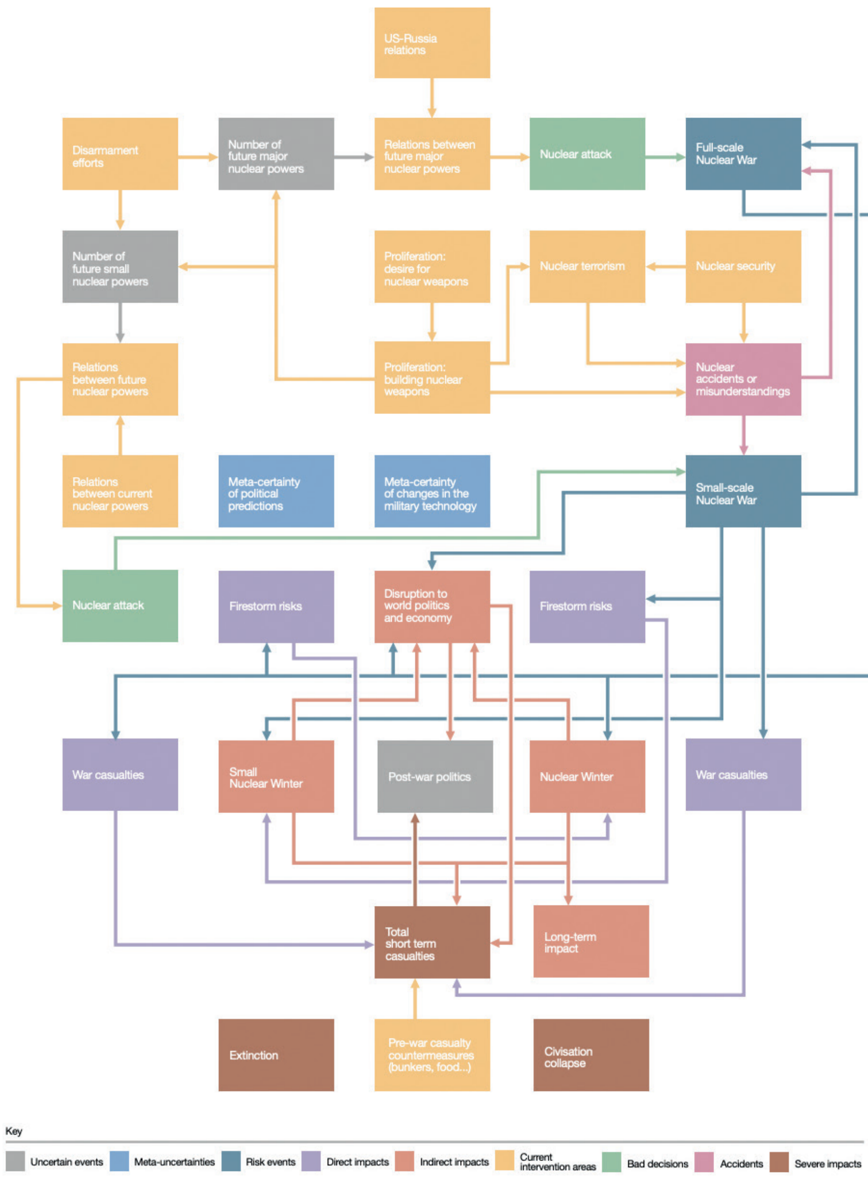
1 One of the first articles to engage with this subject is Matheny, J. G. (2007). Reducing the Risk of Human Extinction. *Risk Analysis.* 27: 5, 1335–1344. https://doi.org/10.1111/j.1539-6924.2007.00960.x. One of the first substantive analyses is Bostrom, N. & Cirkovic, M. (eds.). (2008). *Global Catastrophic Risks* (Oxford: Oxford University Press).

2 See Turchin, A., & Denkenberger, D. (2018). Global catastrophic and existential risks communication scale. *Futures.* 102, 27-38. **Link:** https://doi.org/10.1016/j.futures.2018.01.003. In the Anthropocene age, most catastrophic and existential risks arise from human activity, including the non-zero risk of nuclear war. Bostrom, N. (2013). Existential risk prevention as global priority. *Global Policy.* 4: 1. **Link:** http://www.existential-risk.org/concept.pdf.

Research has also demonstrated the pervasive uncertainty surrounding low-probability, high consequence global catastrophic risks, making it challenging to predict their likelihood or precise impacts. This body of research also highlights the importance of effective risk governance, international cooperation, policy coordination, and information-sharing mechanisms at the global level to address shared risks and facilitate collective action.

Pamlin, D. & Armstrong, S. (2015). Global Challenges: 12 Risks that Threaten Human Civilization. Global Challenges Foundation. Link: https://www.researchgate.net/publication/291086909_12_Risks_that_threaten_human_civilisation_The_case_for_a_new_risk_category

In this report, Pamlin and Armstrong map the risk of nuclear violence as follows:



Bostrom, N. (2002). Existential Risks: Analysing Human Extinction Scenarios and Related Hazards. ***Journal of Evolution and Technology.*** **9.** **Link:** https://jetpress.org/volume9/risks.html

Bostrom is a pioneer of the study of existential and catastrophic risks. His earlier research demonstrates four ways in which existential risks are qualitatively different to other types of risks and hazards that human societies have faced:

1. Dealing with existential risks cannot, by definition, involve trial-and-error because there is no opportunity to learn from errors if extinction follows failure. Instead, a proactive approach is required through preventive steps.
2. We cannot rely on our current institutions, moral norms, social attitudes or national security policies that have developed in response to managing non-existential risks because we have no experience with existential risks.
3. Reductions in existential risks are global public goods and require international cooperation to address, but this can be very difficult. However, privileging state sovereignty is not a legitimate excuse for failing to mitigate them.
4. If we take into account the welfare of future generations, the harm done by existential risks is multiplied by another factor.

Addressing the catastrophic and potentially existential risk posed by nuclear violence therefore requires new ways of thinking and acting.

Pegram, T. & Kreienkamp, J. (2019). Governing Complexity Design Principles for Improving the Governance of Global Catastrophic Risks. Research Policy Brief. Global Governance Institute. **Link:** https://www.ucl.ac.uk/global-governance/sites/global-governance/files/governing_complex_global_catastrophic_risks_ggi_policy_brief_nov2019.pdf

The authors demonstrate the increasing complexity of global catastrophic risks. This makes predictions very difficult and introduces significant uncertainties because relationships in complex systems do not follow linear and controllable patterns. They show that global catastrophic risks are about the breakdown of complex systems, i.e. how breakdowns in part of one system of global politics, for example energy production, can have cascading effects across multiple global social, technological and ecological systems because of the ways in which these systems are now so tightly coupled.

However, the authors argue that we don't actually know very much about the breakdown of global systems that involve many interacting elements. This is in part because we do not have the data for estimating the relative probabilities that a system will evolve along one pathway or another. Complex systems can experience rapid, irreversible and system-wide change if interacting feedback loops drive the system towards a 'tipping point' – a critical threshold after which a minor trigger can result in system-wide cascading failures.

Homer-Dixon, T., Walker, B., Biggs, R., et al. (2015). Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society.* 20: 3.
Link: https://www.jstor.org/stable/26270255.

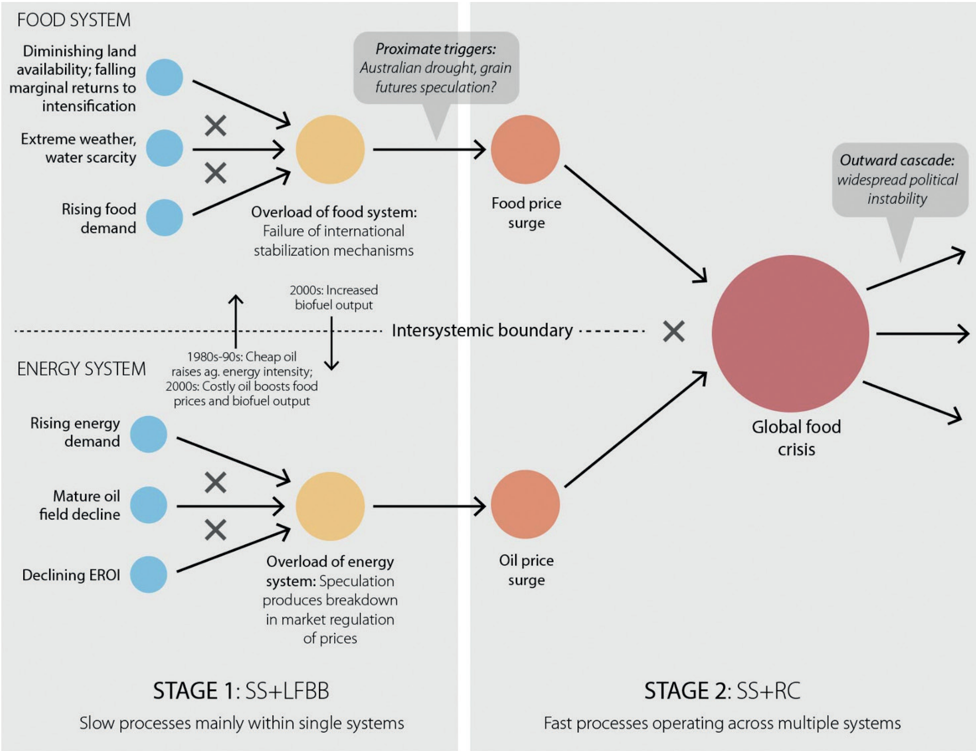
The authors show that recent global crises, especially several that occurred simultaneously in 2008 to 2009, reveal an emerging pattern of systemic crises. They identify the deep causes, processes, and outcomes of this pattern, which they call 'synchronous failure'. They show how multiple stresses can interact within a single social-ecological system to cause a shift in the system's behaviour. They do this by showing how simultaneous shifts in several largely discrete social-ecological systems can interact to cause a much bigger 'inter-systemic' crisis that can then rapidly spread across multiple system boundaries to the global scale.

They argue that two major changes in world politics since the 1950s have brought this about. First is the increase in the scale and speed of connectivity between human technological, economic, and social systems that has increased the size of the overall systems of which each discrete system is a part. Second, the global economy has expanded nearly 20-fold since the 1950s resulting in a massive increase in the use and degradation of the Earth's natural resources and systems that are now under enormous stress and exhibiting a higher frequency of extreme behaviour. The outcome is the emergence of a single, tightly coupled human social-ecological global system for the first time in human history.

These global trends enable the synchronous failure of global systems in three major ways.
1. They generate multiple simultaneous stresses affecting human societies. These stresses build their force slowly yet are potentially very powerful over time.
2. They contribute to conditions favouring synchronous failure by increasing the risk of large and abrupt systemic disruption and by helping such disruptions propagate farther and faster through global networks.
3. They can contribute to conditions favouring synchronous failure by reducing the coping capacity of societies.

Each of these processes usually operates in conjunction with at least one of the other two; that is, each is rarely seen in isolation. This research highlights the context in which the effects of multiple nuclear detonations will be felt. It is a very different context to that of the 1950s when nuclear deterrence theory emerged and became embedded in the strategic cultures of nuclear-armed states, and a very different context to the 1980s when the threat of nuclear war prompted fresh engagement with the effects of nuclear violence.

This diagram from the authors shows how crises in the food and energy systems caused a much bigger global food crisis.



Wernli, D., Böttcher, L., Vanackere, F., et al. (2023) Understanding and governing global systemic crises in the 21st century: A complexity perspective. *Global Policy,* 14, pp. 207-228. Link: https://doi.org/10.1111/1758-5899.13192

The authors examine the role of complexity science in understanding global systemic crises. Complexity science is not a unified theory but a collection of concepts, theories, and methods that are influencing a range of scholarly disciplines. Many insights come from the study of physical, biological, and ecological systems but complexity science is increasingly used to improve our understanding of social and intertwined social-ecological systems.

A growing interconnectivity has enabled the emergence of systemic risks because it has not been accompanied by a fundamental reform of global governance. While the world has experienced several systemic events with global repercussions, the concept of 'systemic crisis' has been mainly used in the context of financial and economic crises, particularly in the wake of the 2008 global financial crisis.

These authors also show that most crises in complex systems are driven by diffusion across tightly-coupled networks and together with feedback loops. However, they also argue that systemic crises can have long-term impacts with the potential for collapse of some parts of the economy, social systems, and society. In addition, they find that the rapid succession of systemic crises so far this century suggests crises roll into each other such that a new crisis unfolds in societies in which the effects of previous crises have not yet dissipated. They argue that drivers of systemic crises are becoming embedded and giving rise to a situation of 'permacrisis'.

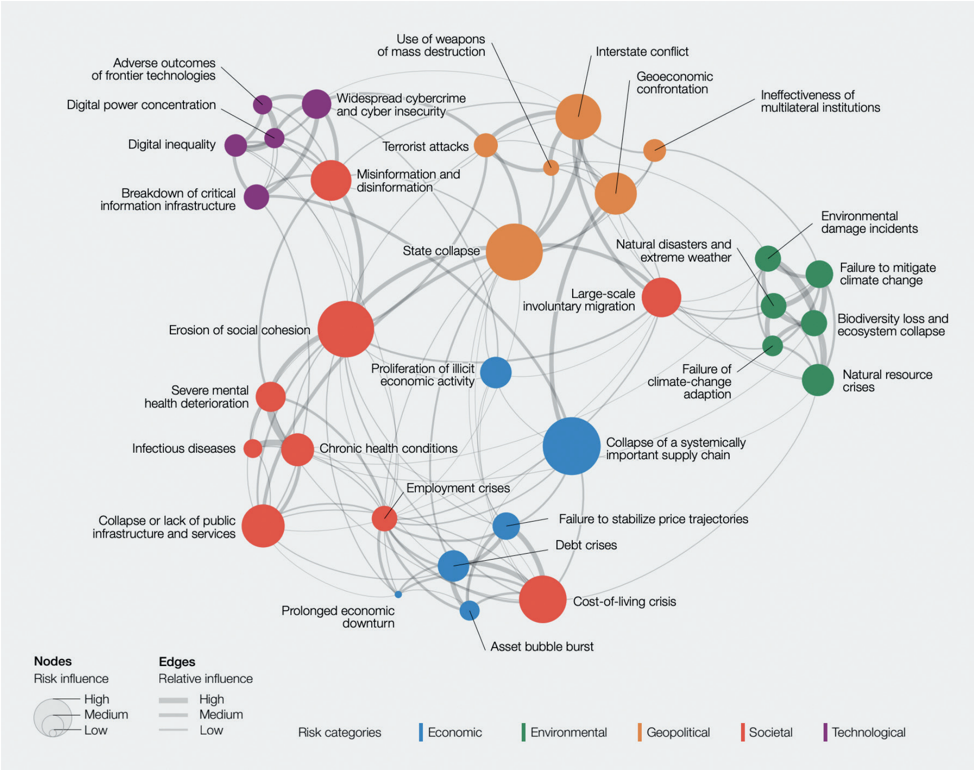
Helbing, D. (2013). Globally networked risks and how to respond. *Nature* 497.
Link: https://doi.org/10.1038/nature12047**.**

Helbing reviews recent scholarship on systemic risk and 'complex dynamical systems', and shows that: i) disasters may result from gradual changes in a system until a 'tipping point' is reached and the stability of the system collapses; ii) 'extreme events' can be a result of the inherent dynamics of a system rather than something caused by an unexpected event that is external to the system; iii) abrupt systemic failures can result from interdependencies between networks; iv) strongly-coupled systems can change very fast - too fast to allow for organisational and human understanding and adequate responses; v) extreme events tend to occur more often than expected in strongly-coupled systems.

He also shows that risk analysis as the systematic study of risks, including global catastrophic risks, suffers from a number of shortcomings. These include: i) Estimates for rare events are often poor; ii) the likelihood of coincidences of multiple unfortunate, rare events is often underestimated even though there is a huge number of possible coincidences; iii) human factors, such as negligence, irresponsible or irrational behaviour, greed, fear, revenge, perception bias, or human error are still often underestimated; iv) common assumptions about risk and uncertainty are often not questioned enough so that "Some of the worst disasters have happened because of a failure to imagine that they were possible, and thus to guard against them".

Helbing observes that "Today's strongly connected, global networks have produced highly interdependent systems that we do not understand and cannot control well. These systems are vulnerable to failure at all scales, posing serious threats to society, even when external shocks are absent. As the complexity and interaction strengths in our networked world increase, man-made systems can become unstable, creating uncontrollable situations even when decision-makers are well-skilled, have all data and technology at their disposal, and do their best."

The Global Risks Report (2023). World Economic Forum.
Link: https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf



Source: World Economic Forum, Global Risks Report 2023, p. 10.

Finally, the World Economic Forum's 'Global Risks Report' unpacks global risks and locates nuclear war (at the confluence of 'Use of WMD' and 'Interstate Conflict') in the context of the full panoply of global systematic risks.

The report is based on Forum's annual Global Risks Perception Survey of 1,200 experts across the Forum's network. It shows that "Climate and environmental risks are the core focus of global risks perceptions over the next decade – and are the risks for which we are seen to be the least prepared", but it also unpacks the risk of polycrisis: "Eroding geopolitical cooperation will have ripple effects across the global risks landscape over the medium term, including contributing to a potential polycrisis of interrelated environmental, geopolitical and socioeconomic risks relating to the supply of and demand for natural resources." Within this global interconnected risk landscape, the report notes the continuing "risk of accidental, miscalculated or deliberate clashes, with devastating results" between nuclear-armed states.

2 Consequences of nuclear violence

ENVIRONMENTAL EFFECTS OF NUCLEAR DETONATIONS

2.1 Environmental effects of nuclear detonations

Over the past 15 years, the scientific community has generated new research findings on the environmental effects of nuclear weapons detonations. This research lent considerable support to the 'humanitarian initiative on nuclear weapons' and the TPNW. This briefing summarises this research that has been published in peer-reviewed scholarly journals, academic books and NGO reports.

The first set of scientific findings on the effects of smoke generated by fires caused by nuclear detonations leading to an extended global cooling labelled 'nuclear winter' and capable of causing the worldwide collapse of agriculture was produced in the 1980s.[1] The computers and simulations were primitive by today's standards and contemporary research on nuclear winter did not restart until 2007 with far more powerful modelling resources. Much of this work has been undertaken by Brian Toon, Professor and Chair of the Department of Atmospheric and Oceanic Sciences and a member of the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder, Alan Robock, Professor of Atmospheric Science at Rutgers University in New Brunswick, New Jersey, and Rich Turco, Professor of Atmospheric Science at the University of California, Los Angeles.

Many of the articles summarised below use the scenario of a nuclear war between India and Pakistan in which each state detonates 50 Hiroshima-sized bombs with an explosive yield of 15 kilotons (kt). In this scenario, the firestorms caused by detonations in cities generate an enormous amount of soot and particulates. In the scientific vernacular, this is called 'black carbon'. The amount of soot produced is calculated using computer models and measured in teragrams (Tg). 1 Tg is 1 million tons. The India-Pakistan scenario is estimated to produce 5 Tg of soot. Later work examines a US-Russia nuclear war in which each state uses 2,200 weapons releasing 150 Tg of soot. More recent work simulates six scenarios: five India-Pakistan scenarios starting with the one outlined above, plus the US-Russia scenario.

Models of the effects of the amount of soot produced and the way it rises into the upper atmosphere, circulates the globe and blocks sunlight are based on advanced climate science models that have been developed to study and model the effects of global heating, volcanic eruptions and massive wildfires. The efficacy of these models has been rigorously tested. As Seth Baum describes it:

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1 The first groundbreaking article on this was Crutzen, P., & Birks, J. (1982). The atmosphere after a nuclear war: Twilight at noon. *Ambio : a Journal of the Human Environment*. 11: 2/3, 114–125. **Link:** https://www.jstor.org/stable/4312777

> "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. 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."[2]

This body of research has cumulatively developed a body of knowledge on the effects of these scenarios on global temperatures, ozone loss, rice, wheat and other crop production, fisheries, and ocean temperatures and acidification. This research is therefore summarised below chronologically to show how this knowledge has developed over the past 15 years or so.

Nevertheless, the effects of nuclear winter are very uncertain. Key unknowns include: the scale of the nuclear war; the extent of firestorms; how much material will burn; how much soot will be injected into the atmosphere; global geographic variation in the human toll and societal collapse; the range of ways in which surviving communities could plausibly respond to nuclear winter; and the extent of societal preparedness.

For a summary, read Robock, A., Xia, L., Harrison, C. S., Coupe, J., Toon, O. B., and Bardeen, C. G.(2023). Opinion: How fear of nuclear winter has helped save the world, so far. *Atmospheric Chemistry and Physics*. 23, 6691–6701.
Link: https://doi.org/10.5194/acp-23-6691-2023.

For a visual representation, watch Tegmark, M. (2022). 'What nuclear war looks like from space?'. Future of Life Institute. **Link:** https://www.youtube.com/watch?v=haab11D7ECs.

Robock, A., Oman, L. & Stenchikov, G.L. (2007). Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences. *Journal of Geophysical Research: Atmospheres*. 112: D13.
Link: https://doi.org/10.1029/2006JD008235

The authors use updated simulations of the climatic effects of soot generated by a nuclear war. Previous simulations were limited by computer power and the available climate models. In this study for the first time, they run an atmosphere-ocean 'general circulation model' to include ocean cooling and conduct continuous multiple 10-year simulations. They show that not only does a nuclear war based on current nuclear

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2 Baum, S. (2015). Winter-safe Deterrence: The Risk of Nuclear Winter and Its Challenge to Deterrence. *Contemporary Security Policy*. 36:1, p. 127. **Link:** https://doi.org/10.1080/13523260.2015.1012346

arsenals (in 2007) still cause a nuclear winter, but that the climate response is much longer than that of earlier results.

They model two scenarios: 1) 150 Tg of soot emitted by the use of the entire current global nuclear arsenal of 5000 megatons of explosive power, about 95% of which is in the arsenals of the United States and Russia, and: 2) 50 Tg of soot emitted by the use of one third of the current nuclear arsenal.

Scenario 1 causes a global average surface cooling of -7 to -8°C that persists for years, and after a decade the cooling is still -4°C. Cooling of more than -20°C occurs over large areas of North America and of more than -30°C over much of Eurasia, including all agricultural regions. Northern hemisphere summer monsoon circulations collapse and global precipitation is reduced by about 45%. Scenario 2 produced climate responses very similar to those for the 150 Tg case, but with about half the size. The maximum global average precipitation reductions for the 50 Tg case are almost exactly half of those from the 150 Tg case. The 50 Tg temperature changes are less than half of those from the 150 Tg case. Both cases produce cooling as large as or larger than that experienced 18,000 years ago during the coldest period of the last Ice Age.

They show that a period of no food production predicted by earlier models needs to be extended by many years, making the impacts of nuclear winter worse than previously thought. In summary, despite a reduction in the number of nuclear weapons since earlier work on nuclear winter was undertaken, the results of these simulations show that nuclear-weapon states still possess more than enough weapons to produce long-lasting, large-scale unprecedented global climate change through nuclear war.

Robock, A., Oman, L., Stenchikov, G.L., Toon, O.B., Bardeen, C. & Turco, R.P. (2007). Climatic consequences of regional nuclear conflicts. *Atmospheric Chemistry and Physics*. 7: 8, 2003-2012. Link: www.atmos-chem-phys.net/7/2003/2007/

The authors model the climatic impact of smoke produced by fires in a nuclear war involving 100 Hiroshima-sized (15 kt) nuclear weapons detonated on cities in South Asia. This study finds that there would be significant cooling and reduction of precipitation lasting years, which would impact the global food supply. In particular, using updated modelling, they show that the changes are more long-lasting because the older models did not adequately represent the ways in which the soot generated by the fires ignited by nuclear explosions rises into the stratosphere. The study also finds that nuclear war at subtropical latitudes results in more solar heating than models for nuclear war in Europe.

The effects on surface temperatures are persistent and result in global average surface cooling of -1.25°C for years. After a decade, it is still -0.5°C. Temperature changes are found to be more drastic over land, consistent with previous findings. A cooling of several degrees occurs over large areas of North America and Eurasia, including most of the grain-growing regions. There would consequently be large reductions in growing seasons in northern and southern hemispheres and a reduction in the length of freeze-free growing seasons would lead to the elimination of crops that did not have enough time to reach maturity. In addition, global precipitation is reduced by 10%, drastically impacting crop growth and reducing the Asian summer monsoon.

They also find that the estimated quantities of soot generated by attacks totalling little more than one megaton of nuclear explosives could lead to global climate anomalies exceeding any changes experienced in recorded history. The global arsenal at the time of writing was about 5000 megatons. This is compounded by increasing urbanisation resulting in megacities with populations exceeding 10 million and therefore higher fuel loadings for fires caused by nuclear detonations.

Mills, M.J., Toon, O.B., Turco, R.P., Kinnison, D.E. & Garcia, R.R. (2008). Massive global ozone loss predicted following regional nuclear conflict. *Proceedings of the National Academy of Sciences.* 105: 14, 5307-5312.
Link: https://doi.org/10.1073/pnas.0710058105

This research uses a chemistry-climate model and new estimates of smoke produced by fires in modern cities to calculate the impact on stratospheric ozone based on an India-Pakistan nuclear war using 100 15kt weapons generating 5 Tg of soot. They report ozone losses of over 20% globally, 25-45% at mid-latitudes, and 50-70% at Northern high latitudes persisting for five years, with substantial losses continuing for five additional years. The reason for ozone depletion is the heating of the stratosphere by smoke which absorbs the solar radiation. The scenario showed that there will be a severe depletion of ozone over populated areas. The increased UV radiation will damage terrestrial and oceanic plants, producing skin cancer, eye damage, as well other health effects in humans and animals. The increase in UV-B radiation will damage aquatic ecosystems, including amphibians, shrimp, fish and phytoplankton, which provide food for a wide range of fish, shrimps and jellyfish. Their findings predict ozone losses significantly greater than previous 'nuclear winter' modelling. In fact, the authors show that the magnitude and duration of the predicted ozone reductions are greater than those calculated in the 1980s for global thermonuclear war scenarios involving yields that exceed those used in this research by factors greater than 1000.

Robock, A. & Toon, O.B. (2010). Local nuclear war, global suffering. *Scientific American.* 302: 1, 74-81. Link: https://www.scientificamerican.com/article/local-nuclear-war/

This article provides a summary of existing research to date on the ecological impact of nuclear detonations. They show using modern computers and modern climate models that not only were the findings about nuclear winter in the 1980s correct but that the effects would last for at least ten years, much longer than previously thought. They show that the smoke from even a regional war between India and Pakistan detonating 50 Hiroshima-sized 15kt weapons each would be heated and lofted by the sun and remain suspended in the upper atmosphere for years, continuing to block sunlight and to cool the earth. They use new models based on satellite observations of forest fires and volcanic eruptions to show how smoke would be lifted into the lower stratosphere and transported around the world. They find that smoke particles would cover all continents within just two weeks, absorbing sunlight. Moreover, once the smoke rises to the upper levels of troposphere and lower levels of stratosphere it would remain there for a significant period in the absence of precipitation to cleanse the air at such altitudes.

Their findings show that precipitation, river flow and soil moisture would all be decreased through reduced sunlight that reduces evaporation and weakens the water cycle. Models showed a 10% reduction in precipitation worldwide, drought in the lower latitudes, and a reduction in Asian monsoon rainfall by up to 40%. There is a global average cooling of about 1.25°C lasting for several years, and even after ten years the temperature was still 0.5°C colder than normal. Less sunlight and precipitation, cold spells, shorter growing seasons and more ultraviolet radiation from ozone loss would all reduce or eliminate agricultural production.

Toon, O.B., Robock, A. & Turco, R.P. (2014). Environmental consequences of nuclear war. *American Institute of Physics Conference Proceedings.* 1596: 1, 65-73.
Link: https://doi.org/10.1063/1.3047679

This research examines the environmental effects of soot produced as a result of nuclear weapons use based on the size of US and Russian nuclear arsenals in 2012. They show that even though nuclear arsenals have reduced significantly since the first generation of nuclear winter studies in the 1980s, the direct effects of using the 2012 arsenals would lead to hundreds of millions of fatalities and indirect effects that would likely eliminate the majority of the human population.

The model is based on the use of 1,000 Russian weapons on the US and 200 warheads on France, Germany, India, Japan, Pakistan, and the UK respectively and the use of 1,100 US weapons on China and Russia. All weapons are 100kt in the simulation. The study finds that a relatively modest 5 Tg of soot would produce the lowest temperatures experienced by the planet in the last 1,000 years. If the soot is increased to 75 Tg (less than half of what can be projected in a hypothetical war using the full US and Russian nuclear arsenals at the time), temperatures would correspond to the last global Ice Age, and precipitation would decrease by more than 25% globally, severely impacting the climate and food production. Modelling a US-Russian nuclear war using 2012 arsenals produces 770 million casualties and 180 Tg of soot. They also show that a hypothetical first strike attack by the US on Russia and China with 2200 weapons with no nuclear retaliation could produce 86.4 Tg of soot, enough to create Ice Age conditions, affect agriculture worldwide, and possibly lead to mass starvation.

Moreover, their new results show that soot would rise to much higher altitudes than previously estimated, and well above the tops of the models used in the 1980s. As a result, the time required for the soot mass to be reduced is much longer and this causes a more dramatic and longer-lasting climate response. The authors state that their work represents the only unclassified study of the consequences of a regional nuclear conflict and the only one to consider the consequences of a nuclear exchange involving US and Russian nuclear arsenals at force levels agreed under the 2002 Strategic Offensive Reductions Treaty (SORT) that were reached by 2012.

Özdoğan, M., Robock, A. & Kucharik, C.J.(2013). Impacts of a nuclear war in South Asia on soybean and maize production in the Midwest United States. *Climatic Change*. 116, 373–387. Link: https://doi.org/10.1007/s10584-012-0518-1

The researchers model the impact on soybean and maize production in the Midwest United States (Iowa, Illinois, Indiana, and Missouri) of an India-Pakistan conflict, in which each of the two states detonates 50 15kt nuclear weapons causing firestorms that inject 5 Tg of soot into the upper atmosphere, on soybean and maize production in the Midwestern US (Iowa, Illinois, Indiana, and Missouri). Soybean and maize are the most abundant crop types grown in the Midwest. They find that maize and soybeans showed notable yield reductions for a decade after the event. Maize yields declined 10-40 %, while soybean yields dropped 2-20 % beyond the natural variation of the crops. The greatest decline was in the five years following the nuclear war. For the next five years, the yield still declined substantially, but less than in the first five years. Yield reduction for both crops was linked to changes in growing period duration and, less markedly, to reduced precipitation and changes in the maximum daily temperature during the growing season.

The authors observe that the US is the world's largest producer and exporter of corn, with the region of the Midwest supplying 80% of production. If yield declines following a South Asian nuclear war, overall production could be depressed for several years following the nuclear conflict, significantly affecting both market conditions and livelihoods.

Stenke, A., Hoyle, C.R., Luo, B., Rozanov, E., Gröbner, J., Maag, L., Brönnimann, S. & Peter, T., (2013). Climate and chemistry effects of a regional scale nuclear conflict. *Atmospheric Chemistry and Physics*. 13: 19, 9713-9729.
Link: https://acp.copernicus.org/articles/13/9713/2013/acp-13-9713-2013.pdf

The researchers use a new 'coupled chemistry climate model' (CCM) to investigate the consequences of a nuclear conflict based on a nuclear conflict scenario between India and Pakistan, each detonating 50 15kt warheads against major population centres, in accordance with previous studies. Their results confirm the findings of Robock et al (reported in 2007), despite using a different simulation model. In fact, the effects of the soot and atmospheric heating were found to be almost exact. In addition, ozone loss and recovery times confirmed the findings of Mills et al. (2008). They confirm that the earth's surface temperatures would drop by several degrees Celsius due to reduction in solar heating, leading to major global cooling. In addition, there is a substantial reduction of precipitation lasting five to ten years, depending on the magnitude of the initial soot release.

A new finding is that extreme cold spells associated with an increase in sea ice formation are found during winter in the northern hemisphere, which expose the continental land masses of North America and Eurasia to a cooling of several degrees. Ice feedback effects are expected to prolong and enhance the climatic response to the soot emissions and have implications for trade shipping routes and global food and fuel supply, especially in the northern hemisphere.

Mills, M.J., Toon, O.B., Lee-Taylor, J. & Robock, A. (2014). Multidecadal global cooling and unprecedented ozone loss following a regional nuclear conflict. *Earth's Future*. 2: 4, 161-176. Link: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2013EF000205

This paper presents the first study of the global impacts of a regional nuclear war with an Earth system model that models atmospheric chemistry, ocean dynamics, and interactive sea ice and land components. It uses the same scenario of a limited, regional nuclear war between India and Pakistan in which each side detonates 50 15kt weapons producing about 5 Tg of soot.

The research findings show that soot emissions would rise even higher than predicted by Robock et al (2007), further compounding the impact upon global temperatures, ozone layer depletion and time it would take for the soot to dissipate. The higher concentration of soot in the atmosphere and its slow removal at higher altitudes leads to increased cooling of the surface compared to previous modelling. Their findings show that global ozone losses of 20-50% over populated areas, levels unprecedented in human history, would accompany the coldest average surface temperatures in the last 1000 years.

They calculate an increase in ultraviolet radiation in summer due to ozone loss by a factor of 3 to 6 over mid-latitudes, suggesting widespread damage to human health, agriculture, and terrestrial and aquatic ecosystems. This means increased instances of skin cancers and painful burns after very short-term exposure to the sun. Additionally, the changes in UV exposure would have an impact on plants attacked by insects and alter the nutrient cycles in the soil. Ozone loss is expected to be around 30-40% in the first five years after nuclear war at mid-latitudes and at 50-60% at northern high altitudes. The average global ozone loss would be 20-25% in the first five years, with a reduction to 8% loss at the end of the first ten years.

They find that the global average surface temperature drops by roughly 1.1 Kelvin (K) in the first year and continues to decrease for five years, reaching a maximum cooling of 1.6 K in year five, two to 2.5 years *after* previous research suggests warming would start again from a maximum cooling of comparable magnitude. After a decade, the calculated global average cooling persists at about 1.1 Kelvin, two to four times that calculated in previous studies. Killing frosts would reduce growing seasons by 10 to 40 days per year for five years. Surface temperatures would be reduced for more than 25 years.

There is also consistent loss in global average precipitation rates persisting for five years. Although the rate of precipitation decline is lower than other research, it is still consistent and long-term, with a reduction of 4.5% after ten years. There would be large reductions in rainfall across Amazon in South America and Southern Africa, as well as American Southwest and Western Australia (20-60%). In addition, sea ice would expand significantly in the Arctic over the first five and ten years. The upper layer of the oceans would experience a prolonged cooling, extending to hundreds of metres in depth.

The combination of years of killing frosts, reductions in needed precipitation, and prolonged enhancement of UV radiation, in addition to impacts on fisheries because of temperature and salinity changes, could exert significant pressures on food supplies across many regions of the globe.

Xia, L., Robock, A., Mills, M., Stenke, A. & Helfand, I. (2015). Decadal reduction of Chinese agriculture after a regional nuclear war. *Earth's Future*. 3: 2, 37-48.
Link: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2014EF000283

This research uses crop simulation models to examine the impact of a regional nuclear war between India and Pakistan on crop production in China over ten years based on 51 locations. The researchers find that in the first year after the regional nuclear war, a cooler, drier, and darker environment would reduce annual rice production by 29%, maize production by 20%, and wheat production by 53%.

Using a range of different agriculture management processes has some effect, but not much: national crop production still reduces 16–26% for rice, 9–20% for maize, and 32–43% for wheat for five years after the nuclear war. This reduction of food availability would continue, with gradually decreasing amplitude, for more than a decade. They find that this dramatic decrease in food supply would cause profound economic and social instability in China. Assuming these impacts are indicative of those in other major grain producers, the authors suggest that regional nuclear war of this type could produce a global food crisis and put a billion people at risk of famine.

Pausata, F.S.R., Lindvall, J., Ekman, A.M.L. and Svensson, G. (2016). Climate effects of a hypothetical regional nuclear war: Sensitivity to emission duration and particle composition. *Earth's Future*. 4: 498-511. **Link:** https://doi.org/10.1002/2016EF000415

The researchers use the standard scenario of an India-Pakistan nuclear war producing 5 Tg of soot. Where the standard scenario simulates transmission of all the soot to the upper troposphere/lower stratosphere in one day, here the researchers model the effects of transmission over a longer period of one month. In addition, they include the effects of the production of a substantial amount of 'particulate organic matter' (POM) by the fires ignited by nuclear weapons detonations.

In general, their model simulations confirm the results of previous studies when making the same assumptions regarding initial conditions. However, they find that in general, extending the period of soot production to one month substantially *reduces* the cooling compared to the one-day case, whereas taking into account POM emissions notably *increases* the cooling and the reduction of precipitation associated with global cooling during the first year following the nuclear war. In addition, while the initial cooling is more intense when including POM emission, the long-lasting effects, while still large, may be less extreme compared to simulations that do not include POM. Specifically, the range of cooling goes from a non-significant decrease in global mean temperature in the case of 5 Tg of soot emitted over a 30-day period to almost 1.5° Celsius cooling by the end of the first year when both soot (5 Tg) and particulate organic matter (45 Tg) are emitted in just one day.

The study highlights that the emission altitude reached by the plume of soot and POM depends on the type of particles emitted by the fires and the duration of the emission. Consequently, the climate effects of a nuclear war are strongly dependent on these parameters.

Helfand, I. (2017). Climate disruption and global famine: Nuclear weapons impact on the environment. In: United Nations, Civil society and disarmament 2016: Civil society engagement in disarmament processes – The case for a nuclear weapons ban. 16-25.
Link: https://front.un-arm.org/wp-content/uploads/2017/03/civil-society-2016.pdf

Helfand, I. (2013). Nuclear Famine: Two Billion People At Risk?. Second Edition. International Physicians for the Prevention of Nuclear War.
Link: https://psr.org/wp-content/uploads/2018/04/two-billion-at-risk.pdf

Helfand's research examines the impact on global food production of the climatic effects of nuclear war. In this study, Helfand uses the scenario above of an India-Pakistan conflict in which each state detonates 50 15kt nuclear weapons causing firestorms that inject 5 Tg of soot into the upper atmosphere. He draws on the research findings outlined above on agricultural disruption. Helfand also makes a key distinction between 'available food', which is the agricultural output, and 'accessible food', which is the amount of food a person can afford to buy. The decrease in agricultural output would drive up the price of remaining food, making it less accessible, especially to those already malnourished.

Helfand examines the likely effects of climatic effects on vulnerable populations as follows (based on 2017 figures):

- 795 million people who are chronically malnourished today have a baseline consumption of 1,750 calories or less per day. Even a 10% decline in their food consumption would put this entire group at risk.
- Several hundred million who enjoy adequate nutrition at this time, but who live in countries that are dependent on food imports, especially grain imports, which would likely collapse.
- 1 billion people in China who have not shared in the economic growth of the last three decades and would have great difficulty buying food given the major shortfalls in Chinese food production that are projected following an India-Pakistan nuclear war.

This is a figure of 'well over' 2 billion people at risk of starvation. Moreover, Helfand suggests that models of agriculture disruption are conservative because they do not factor in the likely decline in availability of fertiliser, pesticides and gasoline after a nuclear conflict, as well as the effects of an increase in UV light. But even these conservative models show a dramatic disruption in the global food chain. In addition, Helfand argues that famines tend to produce epidemic disease and conflict, based on well-studied historical precedents. This would put additional hundreds of millions at risk. Helfand points to the need for further research to examine decline in corn, rice and wheat production and to assess the potential impact of nuclear war upon key crops in other important food producing countries

Reisner, J., D'Angelo, G., Koo, E., Even, W., Hecht, M., Hunke, E., Comeau, D., Bos, R. & Cooley, J. (2018). Climate impact of a regional nuclear weapons exchange: An improved assessment based on detailed source calculations. *Journal of Geophysical Research: Atmospheres*. 123: 5, 2752-2772.

Link: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2017JD027331

This paper is a response to the scholarship above by a team at the US Los Alamos National Laboratory. They use computer modelling to examine the climate impact of a regional India-Pakistan nuclear war. Specifically, they model the multiple phases of the effects of nuclear weapons usage, including the growth and rise of the nuclear fireball,

ignition and spread of the induced firestorm, and comprehensive Earth system modelling of the oceans, land, ice, and atmosphere.
Their simulations find that while the firestorm produces about 3.7 × 109 kg of soot, the vast majority of it never reaches an altitude above weather systems (approximately 12 km). As a result, their simulations produce significantly lower global climatic impacts than assessed in previous studies (summarised above), as soot at lower altitudes is more quickly removed from the atmosphere. Their simulations find significant effects on global surface temperatures are limited to the first five years and are much smaller in magnitude than those shown in earlier works. Contrary to previous studies, none of their simulations produced a nuclear winter effect and their analysis finds that the probability of significant global cooling from a limited exchange scenario as envisioned in previous studies is highly unlikely. They find that the specifics of geography and meteorology for the scenario could significantly decrease the likelihood of a significant global cooling. The key difference in this study is the simulation of fire spread and soot transport in the environment that results from fires initiated by the fireball.

Robock, A., Toon, O.B. and Bardeen, C.G. (2019). Comment on "Climate Impact of a Regional Nuclear Weapon Exchange: An Improved Assessment Based on Detailed Source Calculations" by Reisner et al. *Journal of Geophysical Research: Atmospheres.* 124: 23, 12953-12958.
Link: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019JD030777

The paper is a response to the Los Alamos study above that takes issue with the methodology and findings. In particular, the model used by the Los Alamos team to simulate nuclear detonation fireballs and firestorms is not publicly available and therefore the simulations cannot be recreated. Additionally, the fire model used by the Los Alamos team to simulate mass fires is not typical of the type of fires that can be expected as a result of nuclear detonations on densely populated cities in India and Pakistan, meaning their results underestimate the amount of soot that will rise to the lower stratosphere. Robock et al state that the Los Alamos team's claim that rain would wash out the smoke is not supported by observations of injection of smoke into the stratosphere from forest fires.

Additionally, the Los Alamos team's fire model has not been shown to accurately simulate firestorms observed in Hamburg, Dresden, and Hiroshima during World War II. Moreover, the Los Alamos team did not compare their simulation with previous studies of mass fires, in particular urban mass fires. Overall, the model was found lacking partially due to the arbitrary choices of variables which affected final results and the unavailability of the simulation model and some key parameters that prevent other researchers replicating the study to verify the findings.

Coupe, J., Bardeen, C.G., Robock, A. and Toon, O.B. (2019). Nuclear winter responses to nuclear war between the United States and Russia in the whole atmosphere community climate model version 4 and the Goddard Institute for Space Studies ModelE. *Journal of Geophysical Research: Atmospheres,* 124: 15, 8522-8543.
Link: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019JD030509

This study compares the results of modelling a US-Russian nuclear war that generates 150 Tg of soot from fires using a model used in 2007, with a more up to date model. These two models are the only two comprehensive climate model simulations of this scenario. Despite having different features and capabilities, both models produce similar results. Nuclear winter, with below freezing temperatures over much of the northern hemisphere during summer, occurs because of a reduction of surface solar radiation due to smoke lofted into the stratosphere. However, the newer high-resolution model shows larger temperature and precipitation reductions in the first few years than the 2007 model. Their results confirm that a true nuclear winter occurs in both models as soot blocks sunlight and causes global average surface temperatures to plummet by more than 8° Kelvin.

Both models confirm significant surface temperature drops. Continental North America and Eurasia are 20 Kelvin or more below average for up to three summers after nuclear war. Temperature changes of this magnitude would lead to below freezing summer temperatures for much of the mid-latitudes. Temperatures below 0° Celsius in mid-summer cause a near 90% reduction in the growing season in some locations. The length of the growing season drops below 50 days across much of the interior US and below 100 days for the most agriculturally productive regions in the US. Most of Eastern Europe's growing season is reduced below 50 days, and all parts of Russia have their growing season reduced below 25 days. Hard freezes, where temperatures drop below -4° C, would occur through years 2 and 3 in the summer, making it impossible to grow crops in the US and Russia. Ukraine, Poland, and Germany would suffer similar fates, while in China, only the southeast part of the country would stay above freezing during the summer.

Both models highlight the risk of a crash in global surface temperatures. However, the new model points to a collapse in the summer monsoon in southern Asia which does not return for seven years, a dramatic shift in the variability the El Niño phenomenon, drastic changes to the northern hemisphere winter time circulation patterns, and a climate state that is 0.5 to 1 Kelvin below expected temperatures from before the war with no sign of further warming. In addition, the new climate model points to a shorter lifetime of soot in the atmosphere that alleviates the duration of the most extreme climate effects compared to the 2007 model. Despite this, the cooling for the first few years is more extreme in the new model and temperatures at the end of the simulation suggest a new colder climate state.

Toon, O., Bardeen, C., Robock, A., Xia, L., Kristensen, H., McKinzie, M., Peterson, R., Harrison, C., Lovenduski, N. & Turco, R., (2019). Rapidly expanding nuclear arsenals in Pakistan and India portend regional and global catastrophe. *Scientific Advances*. 5: 10. Link: https://www.science.org/doi/10.1126/sciadv.aay5478

The researchers extend modelling of an India-Pakistan regional nuclear war to reflect the increased size of the two states' nuclear arsenals. They model a hypothetical conflict in 2025 that unfolds over seven days based on the following:

- India: uses 150 nuclear weapons. 15% fail (25), 25 target relatively isolated military bases or industrial facilities, 100 target urban areas or military counterforce targets that are located within urban areas.
- Pakistan: uses 50 5kt weapons against Indian armed forces of which 20% fail. 200 remaining weapons are used but 15% fail. Of the remaining 170, 20 are detonated over isolated military, nuclear or industrial areas, leaving 150 weapons used against India's urban countervalue targets and military counterforce targets located within urban areas.

Strategic weapons for both states are modelled with yields of 15, 50, and 100kt. Modelling in 2007 of a nuclear war between India and Pakistan based on 50 15kt weapons each led to about 22 million immediate fatalities and 44 million total casualties. Modelling for the new scenarios suggests about 50 million people would die if 15kt weapons are used, almost 100 million if 50kt weapons are used, and about 125 million if 100kt weapons are used.

Models predict global average precipitation losses from 15 to 30% for the new scenario over the range of possible yields of 15kt weapons (producing 16.1 Tg of soot), 50kt weapons (producing 27.3 Tg of soot), or 100kt weapons (producing 36.6 Tg of soot). Global average surface temperature drops between 1.25° and 6.5° Celsius over several years. These perturbations reach their peak about three years after the conflict and are near the peak value for about four years. It takes more than a decade for temperatures and precipitation to return to normal.

Modelling the 50kt scenario shows that cooling of the northern hemisphere continents is stronger than that of the southern hemisphere with temperature drops greater than 10° Celsius across North America and Europe north of about 30° latitude, cooling up to 5° Celsius over all continents, and a decrease in ocean temperatures in many regions by an average of 5° Celsius. Of greater significance to surviving populations are the large decreases in rainfall predicted over densely populated regions such as India and central China where precipitation almost ceases. The US Northeast and Midwest lose more than 50% of their rainfall.

Lovenduski, N.S., Harrison, C.S., Olivarez, H., Bardeen, C.G., Toon, O.B., Coupe, J., Robock, A., Rohr, T. and Stevenson, S. (2020). The potential impact of nuclear conflict on ocean acidification. ***Geophysical Research Letters*****. 47: 3.**
Link: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019GL086246

This is the first study of the effects of nuclear conflict on ocean acidification. It looks at ocean acidity using modern simulations. The researchers simulate the effects of soot produced in three India-Pakistan conflict scenarios that inject 5, 27, and 47 Tg of soot, respectively, and one US-Russia conflict scenario that injects 150 Tg of soot.

The researchers find that globally averaged surface ocean pH increases in response to each of the nuclear conflicts and persists for ten years after the conflict. Historically, higher oceanic acidity has been linked to three issues: 1) organisms, which are sensitive to acidity, will be harmed; 2) this will have an impact upon organisms higher in the food chain, which rely on those smaller, sensitive organisms for their nutrition, and; 3) harm to life forms that produce calcium carbonate shells and skeletons (such as corals, mussels, oysters and clams). They also find that the 'aragonite saturation state' decreases. Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. The lower the saturation level, the more difficult it is for organisms to build and maintain their skeletons and shells. This change lasts for more than 15 years post-conflict. These are large and abrupt changes and it is not known how these organisms might respond to such rapid changes. Some previously conducted research points to a negative impact of decreasing aragonite saturation state upon the shell development and growth, leading to the conclusion that calcifying organisms would be negatively impacted by nuclear conflict with long-term ramification for the marine life and food chains leading up to humans.

Jägermeyr, J., Robock, A., Elliott, J., Müller, C., Xia, L., Khabarov, N., Folberth, C., Schmid, E., Liu, W., Zabel, F., Rabin, S. S., Puma, M. J., Heslin, A., Franke, J., Foster, I., Asseng, S., Bardeen, C. G., Toon, O. B., and Rosenzweig, C. (2020). A regional nuclear conflict would compromise global food security. ***Proceedings of the National Academy of Sciences*****. 117-13, 7081-81. Link:** https://doi.org/10.1073/pnas.1919049117

The researchers model the impact on the global food production system of an India-Pakistan conflict in which each state detonates 50 15kt nuclear weapons causing firestorms that inject 5 Tg of soot into the upper atmosphere. The study addresses research questions that remain unresolved from previous studies of agricultural consequences of nuclear war: 1) Where, and to what degree, would global staple crop production be affected by a limited nuclear war?; 2) How large are the main sources of uncertainty associated with the crop response?; 3) To what extent would trade dependencies impair food supply globally?

They find that global caloric production from maize, wheat, rice, and soybean falls by 13 (±1)%, 11 (±8)%, 3 (±5)%, and 17 (±2)% over five years. Total single-year losses of 12 (±4)% quadruple the largest observed historical anomaly and exceed impacts caused by historic droughts and volcanic eruptions. Maize is particularly important as "the linchpin of the global food system". The researchers find that the US and Canada (currently providing over 40% of global maize production) would face 17.5% (±2.4%) production losses, China and East Asia (18% of global production) 6.3% (±1.2%), Europe (15% of global production) 16.7% (±5.5%), and Russia (1.8% of global production) 48.2% (±4.5%). The largest global single-year loss for maize is 14.1% (±2.6%) in year four after the conflict.

They also find that the colder temperatures produced by the climatic effects of the nuclear war are the primary cause of these changes with the largest effects in northern temperate regions (US, Europe, and China) for 10 to 15 years. By year five, maize and wheat availability would decrease by 13% globally and by more than 20% in 71 countries with a total population of 1.3 billion people.

The effect of crop production losses that are concentrated primarily in the northern hemisphere are transmitted globally through the international food trade system. These effects are especially severe because the modelling shows that many of the most important cereal grain exporters are disproportionately impacted, including the US, Canada, Europe, Russia, China, and Australia. Current grain reserves are shown to largely be depleted within one year after the conflict, which results in vulnerabilities of national food supplies in subsequent years.

Scherrer, K. J. N., Harrison, C. S., Heneghan, R. F., Galbraith, E., Bardeen, C. G., Coupe, J., Jägermeyr, J., Lovenduski, N. S., Luna, A., Robock, A., Stevens, J., Stevenson, S., Toon, O. B., and Xia, L. (2020). Marine wild-capture fisheries after nuclear war. *Proceedings of the National Academy of Sciences*. 117: 47, 29748-29758.
Link: https://doi.org/10.1073/pnas.2008256117

The researchers simulate the climatic effects of six war scenarios on fish biomass and catch globally and also how either rapidly increased fish demand (driven by food shortages) or decreased ability to fish (due to infrastructure disruptions), would affect global catches. The scenarios are five India–Pakistan scenarios of increasing intensity (between 5 and 47 Tg of soot) and one substantially larger US–Russia war that generates 150 Tg of soot.

Simulations show that climatic changes caused by nuclear war generally lead to significant short-term losses in global fish catch and biomass in year two after the conflict. More specifically, in the 5 Tg India-Pakistan case, the global catch decreases by at most 3.6% (±1.4%), occurring in year five after the war. In contrast, in the 150 Tg US-Russia case, the largest catch decrease is 31% (±9%) in year three after the war.

Overall, they find that global biomass and catch fall by up to 18% (±3%) and 29% (±7%) after a US–Russia war — similar in magnitude to the end-of-century declines modelled for unmitigated global warming. When war occurs in an overfished state, increasing demand increases short-term (one to two years) catch by at most about 30% followed by precipitous declines of up to approximately 70%.

Fish and other seafood provide almost 20% of the animal protein consumed by the global human population, out of which wild-caught seafood—the focus of this study—make up approximately one-half. They note that, based on previous studies, climatic changes caused by nuclear detonations could lead to decreased crop production on land and a general decrease in caloric supply. This is likely to raise demand for wild-capture fish as a source of animal protein, leading to an increase in price and intensified fishing. After an initial increase in catch, biomass is depleted, driving a fishery crash in all scenarios that lasts until the end of the simulation (15 years). However, if the war induces a substantial decrease in fishing, then global catches initially decrease but fish biomass then rapidly begins to recover.

In summary, climatic changes caused by nuclear war have an overall negative effect on fisheries that increases with the amount of soot injected into the upper atmosphere, despite positive impacts in some subtropical regions. The results also suggest that the marine fish catch is relatively more robust to the effects of a nuclear conflict than land-based food production.

Coupe, J., Stevenson, S., Lovenduski, N.S. et al. (2021). Nuclear Niño response observed in simulations of nuclear war scenarios. *Communications: Earth & Environment*. 2, 18. Link: https://doi.org/10.1038/s43247-020-00088-1

The researchers examine the effects of global cooling resulting from nuclear war on the physical and biological state of the post-war oceans, specifically the El Niño-Southern Oscillation (ENSO). The El Niño-Southern Oscillation is the largest naturally occurring perturbation to Pacific Ocean circulation and biogeochemistry, alternating between warm El Niño and cold La Niña events with a period of roughly three to seven years, with profound impacts on marine productivity and fisheries.

The authors simulate six nuclear war scenarios and show that global cooling can generate a large, sustained response in the equatorial Pacific, resembling an El Niño but persisting for up to seven years. The El Niño following nuclear war, what the authors call a 'Nuclear Niño', is characterised by a sudden increase in westerly surface winds along the western and central equatorial Pacific in the month after the war and the complete disruption of the normal circulation pattern of the equatorial Pacific Ocean. They show that the physical response of the tropical Pacific to a global nuclear war is extreme, and that long persistence of these circulation changes would have sustained and severe impacts on marine productivity and associated food security implications. In particular, the researchers find that reductions in sunlight due and ocean circulation changes would cause a 40% reduction in equatorial Pacific phytoplankton productivity that drives marine ecosystems and fisheries. These results indicate nuclear war could trigger extreme climate change and compromise food security beyond the impacts of crop failure.

Bardeen, C. G., Kinnison, D. E., Toon, O. B., Mills, M. J., Vitt, F., Xia, L., et al. (2021). Extreme ozone loss following nuclear war results in enhanced surface ultraviolet radiation. *Journal of Geophysical Research: Atmospheres*. 126.
Link: https://doi.org/10.1029/2021JD035079

In this study, the authors repeat previous simulations of a regional nuclear war between India and Pakistan using 44 15kt-weapons against urban targets in a war lasting three days that produces 5 Tg of soot, and a global nuclear war between the US and Russia, using current arsenals over seven days, that produces 150 Tg of soot. The simulations are focused on the changes to ozone and surface ultraviolet (UV) light. For the first time with a modern climate model, the authors simulate the effects on ozone chemistry and surface UV caused by absorption of sunlight by smoke. They show that this could lead to a loss of the protective ozone layer taking a decade to recover and resulting in several years of extremely high UV light at the surface further endangering human health and food supplies.

Simulations show a peak ozone loss of about 25% two to three years after the war for the India-Pakistan scenario with much larger losses of up to 55% at high latitudes. This is inline with earlier studies. In the US-Russia scenario, the researchers find much greater ozone loss than was predicted in the 1980s, with a peak global average loss of 75% with losses lasting for 15 years. In this scenario, while the ozone loss is extremely large, the smoke injection into the atmosphere from the nuclear detonations is so big that it leads to reduced UV at the surface for the first few years following the war. The rate of ozone recovery lags the pace of the natural process of smoke removal from the atmosphere leading to several years of very high surface UV, with a UV Index over 35 following a global nuclear war. In comparison, the World Health Organisation advises against being outside during midday hours for a UV index over 8 and describes a UV index of 11 as ‘extreme’.

Xia, L., Robock, A., Scherrer, K. et al. (2022). Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection. *Nature: Food*. 3, 586–596.
Link: https://doi.org/10.1038/s43016-022-00573-0

The authors use climate, crop and fishery models to estimate the impacts of six nuclear war scenarios by predicting the total food calories available in each nation post-war after stored food is consumed. They show that nuclear wars that inject more 5 Tg of soot into the atmosphere would lead to mass food shortages, and livestock and aquatic food production would be unable to compensate for reduced crop output, in almost all countries. The scenarios assume international trade in food is suspended as food-exporting states halt exports in response to declining food production.

The researchers' simulations show that more than 2 billion people could die from nuclear war between India and Pakistan, and more than 5 billion could die from a war between the United States and Russia. African and Middle Eastern countries would be severely affected.

Soot (Tg)	No. of weapons	Yield (kt)	Number of direct fatalities	Number of people without food at the end of year 2
5	100	15	27,000,000	255,000,000
16	250	15	52,000,000	926,000,000
27	250	50	97,000,000	1,426,000,000
37	250	100	127,000,000	2,081,000,000
47	500	100	164,000,000	2,512,000,000
150	4,400	100	360,000,000	5,341,000,000
150	4,400	100	360,000,000	[a]5,081,000,000

[a] Assumes total household waste is added to food consumption.

The last column is the number of people who would starve by the end of Year 2 after a nuclear war when the rest of the population is provided with the minimum amount of food needed to survive, assumed to be a calorie intake of 1,911 kcal per person per day, and allowing for no international trade.

The researchers note that farming adaptations and cultivation of alternative food sources (such as mushrooms, seaweed, insects, and single cell proteins) could reduce the negative impact from a simulated nuclear war, but it would be challenging to make all the shifts in time to affect food availability in Year 2 after the nuclear war. In sum, the reduced light, global cooling and likely trade restrictions after nuclear wars would be a global catastrophe for food security. The negative impact of climate perturbations on the total crop production can generally not be offset by livestock and aquatic food.

Harrison, C. S., Rohr, T., DuVivier, A., Maroon, E. A., Bachman, S., Bardeen, C. G., et al. (2022). A new ocean state after nuclear war. ***AGU Advances,*** **3 4.**
Link: https://doi.org/10.1029/2021AV000610

The authors simulated climate impacts of six nuclear war scenarios. The research shows for the first time that the ocean would enter a new biogeochemical and ecosystem state as a result of global cooling. In all six scenarios, the global cooling that results leads to an expansion of sea ice into populated coastal areas and decimation of ocean marine life. In all scenarios, the ocean cools rapidly but does not return to the pre-war state when the soot is eventually removed from the atmosphere through natural processes. Instead, the ocean takes many decades to return to normal, and some parts of the ocean would likely stay in the new state for hundreds of years or longer.

In the US-Russia scenario, peak Arctic sea ice extent expands by 10 million km^2, covering over 50% more area, including normally ice-free coastal regions important for fishing, aquaculture, and shipping across the northern hemisphere. When the cooling event ends, Arctic sea ice is left in a new state that the authors call a 'Nuclear Little Ice Age." Marine ecosystems would be highly disrupted by both the initial changes to oceans and the resulting new ocean state, resulting in impacts to marine ecosystems lasting for decades. They suggest that the rapid declines in ocean temperature together with other factors such as reduced production of phytoplankton could lead to collapses of marine food-chains.

Coupe, J., Harrison, C., Robock, A., DuVivier, A., Maroon, E., Lovenduski, N. S., et al. (2023). Sudden reduction of Antarctic sea ice despite cooling after nuclear war. ***Journal of Geophysical Research: Oceans.*** **128: 1.**
Link: https://doi.org/10.1029/2022JC018774

This research is the first analysis of impacts of a nuclear winter on Antarctic sea ice through climate modelling experiments. It is based on climate model simulations of six nuclear war scenarios: five India and Pakistan nuclear war scenarios are considered which involve the injection of 5, 16, 27.3, 37, and 46.8 Tg of soot into the upper atmosphere respectively. These simulations are each run for 15 years. The sixth scenario is a US and Russia scenario that injects 150 Tg of soot into the upper atmosphere based on the detonation of 3,100 to 4,400 nuclear warheads with yields between 100 and 500 kilotons targeted at military and industrial areas in the US and Russia. This simulation is run for 30 years. The findings confirm that a large nuclear war would cause rapid global cooling leading to increased sea ice in the northern hemisphere. However, sea ice in the southern hemisphere actually shrinks in the two to six years after a very large nuclear war, mainly caused by a change in the winds around Antarctica. Smoke heats the upper atmosphere and the westerly winds around Antarctica shift closer to the coast. The wind shift causes the top layer of the ocean to move away from the coast, which brings up relatively warm water from below, melting sea ice during summer and inhibiting sea ice growth during the winter. In smaller nuclear war simulations with lesser amounts of global cooling, a sudden decline in Antarctic sea ice extent and volume does not occur, indicating a certain threshold may be required to trigger this response. Reduced Antarctic sea ice extent in a nuclear winter could impact ecosystems that rely on sea ice and exacerbate the ecosystem impacts that are already likely to occur from significantly reduced sunlight and photosynthesis.

HUMANITARIAN CONSEQUENCES OF NUCLEAR DETONATIONS

2.2 Humanitarian consequences of nuclear detonations

A substantial body of social science research has examined the effects of nuclear detonations on people and societies. This research builds on decades of work but has produced new findings over the past 15 years. It can be divided into four broad areas: 1) the effects of the atomic bombings of Hiroshima and Nagasaki in August 1945; 2) the effects of nuclear testing; 3) the capacity of the international humanitarian system to respond to a nuclear detonation; and 4) simulation studies of fatalities in a range of nuclear war scenarios.

Hiroshima and Nagasaki

International Committee of the Red Cross (ICRC) in cooperation with the Japanese Red Cross Society (2015). 70 Years on Red Cross Hospitals still treat Thousands of Atomic Bomb Survivors. **Link:** https://www.icrc.org/en/document/70-years-red-cross-hospitals-still-treat-thousands-atomic-bomb-survivors

This report shows that 70 years after the dropping of the atomic bombs on Hiroshima and Nagasaki, the Japanese Red Cross hospitals in those cities still treat several thousand victims each year for cancers and illnesses attributable to those attacks.

The Hiroshima Atomic-Bomb Survivors Hospital treated 4,657 individual officially recognised atomic bomb survivors between 1 April 2014 and 31 March 2015. Their care involved 62,130 outpatient visits and 34,807 inpatient admissions. Of the atomic bomb survivor deaths that occurred in the hospital from April 2013 to March 2014, nearly two-thirds (63%) were attributed to malignant tumours (cancer), of which the primary types were lung cancer (20%), stomach cancer (18%), liver cancer (14%), leukaemia (8%), intestinal cancer (7%) and malignant lymphoma (6%).

In Nagasaki, the Japanese Red Cross Nagasaki Genbaku Hospital treated 6,030 officially recognised survivors as outpatients and 1,267 as inpatients between 1 April 2014 and 31 March 2015. Their care required 36,260 outpatient visits by survivors and 23,865 outpatient visits by their children, underlining concerns about second-generation health effects of nuclear weapons. The Nagasaki hospital also managed 18,187 inpatient visits by survivors and 12,878 visits by children of survivors. In the Nagasaki hospital, 56% of atomic bomb survivor deaths from April 2013 to March 2014 were attributed to cancers (lung cancer (38%), liver cancer (12%) and stomach cancer (9%)). In addition, cancers of the colon, lymph system, gall bladder and pancreas together accounted for 24% of cancer deaths by survivors.

They find that the psychological impact of exposure to the atomic bombings is also significant, even among healthy survivors. Studies show long-lasting psychological instability, including depression and post-traumatic stress disorder (PTSD) among many survivors. Radiation fear is a common clinical problem when physicians examine survivors' health condition once a year in accordance with Japanese Government policy.

Malloy, S. (2012). "A Very Pleasant Way to Die": Radiation Effects and the Decision to Use the Atomic Bomb against Japan. *Diplomatic History*. 36: 515-545.
Link: https://doi.org/10.1111/j.1467-7709.2012.01042.x

Malloy examines the extent of knowledge of the effects of radiation from the detonation of atomic bombs when the US detonated bombs above Hiroshima and Nagasaki in August 1945. He surveys pre-Hiroshima knowledge of radiation effects in the US scientific community and shows that most of the immediate and long-term biological effects of radiation on the bombing victims were predictable at the time, even if still imperfectly understood. He also shows that this knowledge played little role in the decision to use the atomic bomb driven in part by compartmentalisation of knowledge in the Manhattan Project, and the focus on models of the effects of A-bombs that focussed only on the blast. The US political leadership was therefore not informed that the weapon would continue to sicken and kill its victims long after use. Given vocal opposition in the US in 1943 to the use of a radiological weapon, Malloy argues that such knowledge could have led to different choices on if or how to use the new weapon.

Women, girls and radiation

Olson, M. (2019). Disproportionate impact of radiation and radiation regulation. *Interdisciplinary Science Reviews*. 44: 2, 131-139.
Link: https://doi.org/10.1080/03080188.2019.1603864

Olson shows that the male body is used for generic evaluation of the impact of ionising radiation on human bodies and regulation and nuclear licensing decisions in the US. Yet, findings from 60 years of atomic bomb survivor data show that a system based on adult male tolerance does not represent the human life cycle with respect to harm from radiation exposure. Olson finds that females are more harmed by radiation, particularly when exposed as young girls, than is predicted by use of 'Reference Man' in the US regulatory system. The difference is as much as 7-fold. Since females have been ignored in regulatory analysis, this has resulted in systematic under-reporting of harm from ionising radiation exposure in the global population.

Specifically, Olson finds that children are more likely to be impacted by instances of cancer due to their bodies still growing and cells dividing faster than those of adults and that female bodies are harmed more in every age-of-exposure cohort. The findings are consistent with previous results of similar research. Olson recommends an adoption of a ‘Reference Girl’ (3-4 years old) as a new standard for radiation exposure for children, and changes to public radiation safety regulations.

Folkers, C. (2021). Disproportionate Impacts of Radiation Exposure on Women, Children, and Pregnancy: Taking Back our Narrative. *Journal of the History of Biology.* 54, 31–66. Link: https://doi.org/10.1007/s10739-021-09630-z

Folkers shows that women, children, and pregnancy development are particularly sensitive to exposure from radioactivity, suffering more damage per dose than adult males, even down to small doses. Folkers finds these sensitivities have been routinely devalued by research institutions and regulatory authorities in order to maintain and expand nuclear technology. An institutional focus on maintaining the primacy of nuclear technology has made accurate or meaningful health accounting difficult. This not only makes providing health services to survivor communities problematic, but also complicates proper accounting of the risk of radiation exposure.

The effects of nuclear testing

Ruff, T.A. (2015). The humanitarian impact and implications of nuclear test explosions in the Pacific region. *International Review of the Red Cross*. 97: 899, 775-813. Link: https://doi.org/10.1017/S1816383116000163

This paper shows that there have been slow and incomplete developments towards accountability, care and compensation programmes for those harmed in the processes of building and testing nuclear weapons in countries such as the US, Australia and Fiji. For example, in Australia, where the UK tested nuclear weapons, unresolved issues many decades later include indigenous dispossession, remaining contamination, inadequate clean-up of test sites, and necessary compensation for Aboriginal people, ex-servicemen and civilians for their exposure to radiation, illness and loss.

In the Pacific, Ruff’s review of radiation health effects and the impacts of nuclear testing across the region finds inherent disregard by nuclear-armed states towards the populations impacted by nuclear testing. Programmes to develop, test and deploy nuclear weapons side-lined safety, environmental and health considerations, even by the available knowledge and standards of the time. Nuclear-armed states failed to monitor the effects of nuclear testing on affected populations adequately, and as a result, did not provide the people with sufficient care and follow-up. While some nuclear-armed states have introduced programmes for their own citizens to address the problems and the legacy of their nuclear testing, few have extended care or compensation to the citizens of other countries, including those where nuclear tests were imposed. Where they have, such as the US in relation to the Marshall Islands, it has been insufficient.

Extensive radioactive, chemical and other waste on land, in lagoons and in the ocean remains both at former testing sites and at a network of facilities and infrastructure supporting the nuclear weapons enterprise. Most often, those individuals endangered the most were minorities from indigenous or colonised populations. For indigenous people such as Marshall Islanders, Maohi islanders in French Polynesia and indigenous Australians, Ruff finds that traditional lifestyles, in close physical contact with a natural environment contaminated by nuclear testing, sustained by gathering and hunting of traditional local foods and living in housing made of local materials, are associated with increased radiation exposures. No programmes address the situation and needs of subsequent generations whose lands have been polluted, social and cultural heritage disrupted, and many of whom continue to live in contaminated environments.

Rice, J. & Rice, J. (2014). "Radiation is Not New to Our Lives": The U.S. Atomic Energy Commission, Continental Atmospheric Weapons Testing, and Discursive Hegemony in the Downwind Communities. *Journal of Historical Sociology*. 28: 4, 491-522.
Link: https://onlinelibrary.wiley.com/doi/epdf/10.1111/johs.12076

The authors examine US Atomic Energy Commission (AEC) pamphlets distributed to communities 'downwind' from the Nevada Test Site in 1953, 1955, and 1957 coincident with major test series. They show that the AEC portrayed radioactive fallout as natural, ubiquitous, and controllable. Further, AEC discourse cast officials in a paternalistic role and residents of the rural communities downwind as best served through acquiescence to AEC authority and expertise. They show that empirical evidence regarding the deleterious health effects of atmospheric atomic testing between 1951 and 1962 was understood by then. The researchers provide a recap of two studies in 2002 by the US National Cancer Institute and the US Center for Disease Control on the effects of radiation during the period of US open air nuclear testing from 1951 to 1962. Together, the studies show overall excess cancers of approximately 80,000 cases, of which about 17,000 are predicted to be fatal.

Collin, J.M. & Bouveret, P. (2020). Radioactivity under the Sand: The Waste From French Nuclear Tests in Algeria. ICAN and Observatoire les Armaments.
Link: https://www.boell.de/en/2020/07/08/radioactivity-under-the-sand

This study conducts an inventory of all the nuclear waste materials buried by France in Algeria after conducting a series of nuclear tests in the Algerian Sahara in the 1960s. These materials include everything that may have been contaminated by radioactivity, including tanks and planes. The research finds that France has never revealed where exactly this waste was buried, or how much of it was buried. In addition to these contaminated materials, voluntarily left on site to future generations, there is non-radioactive waste resulting from the operation and dismantling of the sites and radioactive materials emitted by nuclear explosions, such as vitrified sand, radioactive slabs and rocks. Most of this waste was left in the open, without being secured and therefore accessible to the local population, creating a significant health and environmental risk. Neither France nor Algeria have undertaken sufficient measures to protect the population and environment in the affected area. Moreover, Collin and Bouveret note that it is extremely difficult to assess the health effects of radiation exposure on local people since at the time of testing, there was no monitoring of people's health or any medical studies listing the number of cancer cases potentially caused by radiation from the nuclear tests.

Maclellan, N. (2017). *Grappling with the Bomb: Britain's Pacific H-Bomb Tests* (Australian National University Press, Canberra).
Link: https://press.anu.edu.au/publications/series/pacific/grappling-bomb#tabanchor.

Maclellan investigates the effects of British nuclear testing on the British Gilbert and Ellice Islands Colony (GEIC) in the late 1950s, codenamed Operation Grapple. British military and scientific personnel were joined by hundreds of New Zealand sailors, Gilbertese labourers and Fijian troops. The Gilbert Islands later became the state of Kiribati and the Ellice Islands later became the state of Tuvalu. Maclellan finds that British authorities continue to argue that the risk of exposure to radiation was minimised throughout the testing programme. However, the archives reveal that elaborate safety precautions on paper were not matched by actual protection on the ground. Participants in Operation Grapple subsequently reported a range of serious health problems, including many cases of cancer, leukaemia and sterility, which they attribute to their time on Kiritimati/Christmas Island, an atoll now part of the Republic of Kiribati. Maclellan further finds that for reasons of cost, time pressure and cultural arrogance — even racism — the British authorities constantly cut corners on safety and used different standards for radiation exposure for Westerners and Fijians. Unlike the US and France, which have both established compensation schemes for nuclear survivors, the British Government has refused to establish such a scheme for all participants in the Kiribati test programme.

Alexis-Martin, B., Bolton, M.B., Hawkins, D., Tisch, S. & Mangioni, T.L. (2021). Addressing the humanitarian and environmental consequences of atmospheric nuclear weapon tests: A case study of UK and US test programs at Kiritimati (Christmas) and Malden Islands, Republic of Kiribati. *Global Policy*. 12: 1, 106-121.
Link: https://onlinelibrary.wiley.com/doi/full/10.1111/1758-5899.12913

This study examines how the UK and the US handled humanitarian and environmental consequences of atmospheric nuclear weapons tests near Malden and Kiribati Islands. The findings highlight the inadequacy of measures taken, both with regards to survivors' needs and rights and ongoing environmental concerns. They show that the global and national policy response to the humanitarian and environmental legacies of UK and US nuclear weapons tests in Kiribati have been patchwork and inadequate at best. Specifically:

- There has been little systematic radiological monitoring of the test sites and thus, the extent and significance of ongoing contamination is unclear.
- The British military did not monitor the health of many service personnel following the end of their service in the testing programme.
- Fijian soldiers and sailors were treated with even less regard than their British and New Zealand counterparts during the UK test programme.
- Limited independent research into the health outcomes for residents of Kiribati and the New Zealand veterans shows elevated levels of blood cancers and frequencies of genetic damage, which has been attributed to the radiation exposure.

The UK and US authorities claim to have limited the environmental consequences. However, no publicly available data exists, and hence there is no opportunity to verify their claims. There has never been a sufficiently comprehensive, public, and independent analysis of the environmental impact of nuclear testing at Kiritimati or Malden Island. Finally, resources in Kiribati for research into the consequences of the nuclear weapon tests, victim assistance and environmental remediation are severely limited.

Philippe, S., Schoenberger, S. & Ahmed, N. (2022). Radiation Exposures and Compensation of Victims of French Atmospheric Nuclear Tests in Polynesia. *Science & Global Security.* 30:2, 62-94. Link: https://doi.org/10.1080/08929882.2022.2111757

The authors use recently declassified documents, as well as atmospheric transport modelling of radioactive fallout, to show that the French government underestimated the upper-bound estimates of effective doses received by the French Polynesian population. They find the released doses from the 41 atmospheric nuclear weapon tests conducted between 1966 and 1974 have been underestimated by factors of 2 to 10, even without considering all measurement and model uncertainties. As a result, approximately 110,000 people, representing 90% of the French Polynesian population at the time, could have received doses greater than 1 millisievert per year (mSv/yr). Integrating updated dose estimates into France's compensation process would enlarge the pool of eligible claimants by a factor of 10.

The re-evaluation of doses is based on declassified French government documents, including historical archives of the Joint Radiological Safety Service (SMSR) and the Joint Biological Control Service (SMCB). They provide measurement data relating to the internal and external radiation exposures of local populations during the period of atmospheric testing as well as technical information about the size and composition of French radioactive debris clouds. A dose of 1 mSv/yr is the threshold in the French compensation law for victims of past nuclear testing.

Bolton, M. (2022). Human Rights Fallout of Nuclear Detonations: Reevaluating 'Threshold Thinking' in Assisting Victims of Nuclear Testing. *Global Policy*. 13: 1, 76-90. Link: https://doi.org/10.1111/1758-5899.13042

Bolton shows that populations that lived 'downwind' from nuclear tests face ongoing risks from exposure to ionising radiation as well as psychological, social, and cultural distress. However, testing states obscured these humanitarian consequences by claiming that fallout could be contained to specific spatial zones, that there are 'thresholds' below which radiation exposure has negligible health impacts and that socio-political forms of harm should be disregarded.

The research examines responses to French Pacific nuclear testing and finds that access to compensation and other assistance has often been conditioned on 'threshold' radiation exposure criteria that limit affected communities' access to assistance and remedy. Bolton notes that while the scientific consensus concludes there is no safe level of radiation exposure and that fallout circulates in complex, non-linear patterns, 'threshold thinking' remains an underlying assumption in many policies aimed at addressing the radiological effects of nuclear detonations on human bodies and communities. Even though France has acknowledged some negative impacts of nuclear fallout, these acknowledgments serve to limit the state's responsibility for remediation action. Bolton also finds that while the vast majority of focus on the effects of nuclear weapons testing has been on instances of cancer in affected populations, very little has been done to assess the impacts upon coral reefs and psycho-social impacts through anxiety and trauma among the people who have or fear to have been exposed to radiation.

Amundsen, F. and Frain, S.C. (2020). The politics of invisibility: Visualising legacies of nuclear imperialisms. *Journal of Transnational American Studies*. 11: 2.
Link: https://doi.org/10.5070/T8112049588

The authors use the concept of invisibility to examine the legacies of nuclear imperialism across Oceania for indigenous people. The research shows how the experiences of indigenous people living near nuclear test sites have been marginalised through the ways in which nuclear weapons and nuclear programmes have been discursively constructed. It highlights the importance of making the victims of nuclear testing 'visible' to give them the agency that has so far been refused by nuclear-armed states that tested nuclear weapons in the region. They find that government archives are equally guilty of disregarding the humanitarian impact of nuclear weapons testing as they use the same discourses to silence indigenous experiences in official narratives and to justify the existence of nuclear programmes.

Chaizhunusova, N., Madiyeva, M., Tanaka, K. et al. (2017). Cytogenetic abnormalities of the descendants of permanent residents of heavily contaminated East Kazakhstan. *Radiation and Environmental Biophysics*. 56, 337–343.
Link: https://doi.org/10.1007/s00411-017-0717-2

The authors argue that the long-term consequences of Soviet nuclear testing at the Semipalatinsk Nuclear Test Site (SNTS) in Kazakhstan and the appearance of any hereditary effects remain insufficiently studied. This study conducts an assessment and comprehensive cytogenetic analysis of the inhabitants living near the SNTS, and their first and second- generation children. Cytogenetics involves testing samples of tissue, blood or bone marrow in a laboratory to look for changes in chromosomes, including broken, missing, rearranged, or extra chromosomes. They find a higher number of chromosome aberrations in people whose parents permanently lived in the heavily contaminated villages of Dolon and Sarzhal compared to residents in the control area. This indicates that radiation most likely had biological effects on the exposed subjects.

Semenova, Y., Pivina, L., Manatova, A., Bjørklund, G., Glushkova, N., Belikhina, T., Dauletyarova, M., & Zhunussova, T. (2019). Mental distress in the rural Kazakhstani population exposed and non-exposed to radiation from the Semipalatinsk Nuclear Test Site. *Journal of Environmental Radioactivity*. 203, 39-47.
Link: https://doi.org/10.1016/j.jenvrad.2019.02.013

This study, the first of its kind, investigates the rates of depression, anxiety, somatic distress, and fatigue in a rural population of Abayskiy, Borodulikha and Mayskiy districts exposed to radiation from Soviet nuclear testing at the Semipalatinsk Nuclear Test Site in Kazakhstan in comparison with the unexposed population of Kurchum district. The researchers find the prevalence of depression, anxiety, somatic distress and fatigue in the exposed group to be considerably higher than in the control group. They conclude that even though almost 30 years has passed after the closure of the Semipalatinsk Nuclear Test Site, it presents a major public health problem in terms of the negative impact on mental health in the population.

Humanitarian responses to a nuclear detonation

Maresca, L. (2013). The catastrophic humanitarian consequences of nuclear weapons: The key issues and perspective of the International Committee of the Red Cross. In Borrie, J. & Caughley, T. (eds). *Viewing Nuclear Weapons through a Humanitarian Lens* (UNIDIR: Geneva). 131-144.
Link: https://www.un-ilibrary.org/content/books/9789210563666c010

Maresca examines the International Committee of the Red Cross' (ICRC) work on the humanitarian consequences of the use of nuclear weapons. He cites a 2009 ICRC study on the implications of the use of a chemical, biological, radiological or nuclear (CBRN) weapon in terms of the provision of humanitarian assistance.[1] The study led the ICRC to conclude that there is little capacity available at national or international levels to provide meaningful assistance to a substantial portion of survivors of the detonation of a nuclear weapon. Maresca finds that this conclusion still stands.

Specifically, an overwhelming number of people would need immediate treatment for severe and life-threatening wounds that is unlikely to be available in the short term since most of the local medical personnel would be dead or wounded and most medical facilities would be destroyed or unable to function in the area affected by nuclear detonations. Any medical supplies that were not destroyed or contaminated by the blast (for example fluids, bandages, antibiotics, and pain medicines) would be quickly used up. The level of casualties and destruction would also have severe implications for the delivery of humanitarian assistance. The ICRC further finds that most national and international entities have little capacity to deliver the breadth and type of aid that would be required. A further concern is for the safety of assistance providers, especially the risk associated with exposure to ionising radiation. Depending on the levels of radiation, protective measures will have to be implemented, which may simply mean that humanitarian assistance will not be provided.

Bagshaw, S. (2013). Responding to the detonation of nuclear weapons: A United Nations humanitarian perspective. In Borrie, J. & Caughley, T. (eds). Viewing Nuclear Weapons through a Humanitarian Lens (UNIDIR: Geneva). 118-130.
Link: https://doi.org/10.18356/1ddf5574-en

Bagshaw examines the ability of UN humanitarian agencies to respond to the detonation of a nuclear weapon. The effects of nuclear detonations would require the services and expertise of all UN humanitarian agencies and beyond, including the ICRC as well as a range of humanitarian non-governmental organisations, as implementing partners. Responding to a nuclear detonation would almost certainly have implications for each of the main sectors of humanitarian response: health, emergency shelter, camp coordination and management, water and sanitation, food security, nutrition, protection, telecommunications, and logistics. Bagshaw finds that the unprecedented nature and scale of destruction resulting from the use of nuclear weapons would likely render the UN's response extremely difficult, if at all meaningful. Lack of experience of response

1 Coupland R. & Loye, D. (2009). International assistance for victims of use of nuclear, radiological, biological or chemical weapons: time for a reality check? International Review of the Red Cross. 91: 874. **Link:** https://international-review.icrc.org/sites/default/files/irrc-874-5.pdf.

to such an event means there is no precedent or framework to follow. UN agencies would also have to ensure their presence on the ground to coordinate and implement humanitarian operations without putting their staff at unacceptable risk, in particular from radiation exposure and/or retaliatory nuclear strikes. Overall, Bagshaw finds that assessments to date show it is not possible for the UN system to respond effectively to nuclear detonations.

Borrie J., & Caughley, T. (2014). An Illusion of Safety: Challenges of Nuclear Weapon Detonations for United Nations Humanitarian Coordination and Response (United Nations Institute for Disarmament Research (UNIDIR), Geneva).
Link: https://unidir.org/publication/illusion-safety-challenges-nuclear-weapon-detonations-united-nations-humanitarian

This study examines their implications for the UN-coordinated humanitarian system of a nuclear detonation. The UN humanitarian system, led by the Emergency Relief Coordinator (ERC), includes a mosaic of actors of which UN agencies and their capacities are only a part. A nuclear weapon detonation event with mass casualties would lead to the highest level of activation of the UN emergency response system: a rapid "humanitarian system-wide emergency activation", known as "Level 3" within the UN system. In response to the highest level of disasters, humanitarian clusters are established to coordinate the international disaster relief response, with different UN agencies leading on logistics, camp coordination and management, early recovery, education, shelter, emergency telecommunications, food security, nutrition, health, protection, and water, sanitation and hygiene (WASH). The safety of any humanitarian personnel entering or operating in the nuclear detonation-affected zone will be paramount, but data on the scale of the disaster will be difficult to gather.

The study shows that:

1. The current level of awareness within the humanitarian system is generally low about the specificities of nuclear weapon detonation events or its ability to respond to them. There is no coherent framework within the UN system for coordinating a humanitarian response to nuclear weapon detonation scenarios, even at basic levels of preparedness, let alone a large-scale nuclear war.
2. The UN and wider international disaster relief system is unlikely to be able to offer much humanitarian assistance in the immediate aftermath of a nuclear weapon detonation event because of residual radiation, lack of training and equipment for radiological environments, destruction of transport infrastructure (potentially including airports), and firestorms. It would take some time for the humanitarian system to deploy. The immediate needs of the victims in a nuclear weapon detonation event will therefore fall on local and national authorities to the extent they still function. In a highly populated area, the humanitarian need will be vast.

3. Threat or fear of further nuclear weapon detonation events could vastly complicate decision-making about the nature and scale of humanitarian coordination and response, let alone its delivery.

The authors note that they cannot be categorical in stating that a government could not deal within its national resources with the humanitarian consequences of a single nuclear weapon detonation in certain scenarios. However, they support the general conclusion that it is unlikely that any state or international body could address the immediate humanitarian emergency caused by a nuclear weapon detonation in an adequate manner and provide sufficient assistance to those affected. Moreover, it might not be possible to establish such capacities, even if it were attempted.

Sanders-Zakre, A., de Verdier, M. & Lind, J. (2022). No Place to Hide: Nuclear Weapons and the Collapse of Health Care Systems. International Campaign to Abolish Nuclear Weapons.
Link: https://www.icanw.org/report_no_place_to_hide_nuclear_weapons_and_the_collapse_of_health_care_systems

This report examines the extent of healthcare system collapse in the nine nuclear-armed states as well as in one country hosting nuclear weapons on its territory (Germany), following a 100kt nuclear weapon detonation in their respective capital cities. It uses publicly available information about hospitals and their staff and the NUKEMAP simulator to predict the capacity for immediate response to treat victims. The cities examined are Beijing, Islamabad, London, Moscow, New Delhi, Paris, Pyongyang, Tel Aviv, Washington, D.C., and Berlin. The data show that none of these cities would have anywhere near the sufficient healthcare capacity to respond to a nuclear explosion. There would not be enough doctors, nurses, hospital beds or intensive care unit (ICU) beds – even assuming that all available medical professionals are adequately trained in emergency medicine and that every bed listed in each of these cities that is not destroyed during the nuclear attack is unoccupied. Overall, the report finds that no major city or health service is or can be adequately prepared to respond to the needs of people in the immediate aftermath of one 100kt nuclear explosion.

Humanitarian effects of nuclear war

von Hippel, D. & Lisowski. E (2023). Humanitarian Impacts of Nuclear Weapons Use in Northeast Asia: Implications for Reducing Nuclear Risk. Asia-Pacific Leadership Network (APLN).
Link: https://www.apln.network/analysis/special-report/humanitarian-impacts-of-nuclear-weapons-use-in-northeast-asia-implications-for-reducing-nuclear-risk

This study simulates five nuclear use scenarios in Northeast Asia and assesses the number of fatalities:

1. Nuclear weapons use by the DPRK, followed by the US: three 10kt detonations plus one 8kt detonation.
2. First nuclear weapons use by the US, followed by the DPRK and China: 18 total detonations ranging in yield from 8 to 300kt
3. One 10kt weapon detonated by a terrorist group.
4. First nuclear weapons use by Russia, followed by the US: eight total detonations of 150 and 200kt weapons.
5. First nuclear weapons use by China over a Taiwan conflict, followed the US: 24 total detonations ranging in yield from 8 to 300kt.

Estimated Likely Direct and Cancer Deaths in Each of Five Modeled Use Cases

Estimated Likely Deaths	**Prompt** (days to weeks)	**Short-Term** (weeks to months)	**Additional Impact: Firestorms**	**Total Fatalities within 0,5 psi Zone** (Total Population, % Lethality)	**High Radiation Dose** (Fallout) (short-term deaths)	**Radiation-included Cancer** (long-term deaths)
Use Case 1 Airburst: 1, Surface-burst: 2	5,500	5,600	Firestorm Unlikely	**11,000** (41,000, 27%)	Low Fallout	16,000 - 36,000
Use Case 2 Airburst: 11, Surface-burst: 7	1,100,000	810,000	170,000	**2,100,000** (6,200,000, 33%)	11,000 - 1,200,000	480,000 - 920,000
Use Case 3 Surface-burst: 1	82,000	140,000	Small Centralized Firestorm	**220,000** (890,000, 25%)	0 - 1,600,000	410,000 - 560,000
Use Case 4 Airburst: 8	170,000	100,000	15,000	**290,000** (800,000, 36%)	Low Fallout	14,000 - 85,000
Use Case 5 Airburst: 16, Surface-burst: 8	1,500,000	930,000	190,000	**2,600,000** (7,600,000, 35%)	400 - 19,000	96,000 - 830,000

Rodriguez, L. (2019). How many people would be killed as a direct result of a US-Russia nuclear exchange? Rethink Priorities.

Link: https://rethinkpriorities.org/s/Rethink-Priorities-How-many-people-would-be-killed-as-a-direct-result-of-a-US-Russia-nuclear-exchang.pdf

Rodriguez examines likely direct casualties in a US-Russian nuclear war based on current arsenals, targeting strategies, accuracy and survivability of US and Russian warheads, and estimated probability of counter-force (targeting each other's military sites and weapon systems) versus counter-value (targeting cities and national infrastructure) strikes. She calculates an estimated 20 million deaths caused directly by counter-force targeting by the US and Russia and an estimated 104 million deaths caused directly by counter-value targeting by the US and Russia.

Rodriguez, L. (2019). How bad would nuclear winter caused by a US-Russia nuclear exchange be? Rethink Priorities. Link: https://rethinkpriorities.org/s/Rethink-Priorities-How-bad-would-nuclear-winter-caused-by-a-US-Russia-nuclear-exchange-be_-Google-Do.pdf

Rodriguez then examines likely indirect casualties in a US-Russian nuclear war caused by the effects of a nuclear winter. She notes that the modelling is inherently speculative given the uncertainties about the relationship between the amount of smoke injected into the atmosphere by firestorms caused by nuclear detonations, the effects on global temperatures and precipitation, the effects of crop production, and the adaptability of global food production and distribution systems. She estimates that a nuclear exchange between the US and Russia would lead to a famine that would kill 5.5 billion people.

Philippe S., & Stepanov, I. (2023) Radioactive Fallout and Potential Fatalities from Nuclear Attacks on China's New Missile Silo Fields. *Science & Global Security*. Link: https://www.tandfonline.com/doi/full/10.1080/08929882.2023.2215590

The authors examine the radiological effects of a US counterforce nuclear attack on the three new nuclear ballistic missile silo fields China is constructing near the cities of Yumen, Hami, and Ordos as part of a significant expansion of its nuclear arsenal. They assume two 300kt US warheads per silo based on US nuclear targeting strategy. Modelling shows that such an attack would cause tens of millions of Chinese casualties from lethal fallout including in East China. They find that inhabitants of major Chinese cities and provinces, including Beijing, could receive two-week doses of radiation greater than 20 Grays (Gy, the standard international unit measure of radiation) resulting in millions of fatalities, even accounting for protection from sheltering. In particular, the relatively short distance between the Ordos missile field and Beijing and the local winds patterns for the region, suggest that about half of the 21 million inhabitants of the Chinese capital could die following a US counter-force strike, even if given advanced warning to shelter in place. In total, more than 14 million people could die in China from acute radiation sickness (ARS) as unintended but expected humanitarian consequences of a US attack. Fallout would also affect neighbouring countries leading to significant fatalities in North Korea, South Korea, Mongolia, and Japan, among others.

Ainslie, J. (2013) If Britain Fired Trident: The humanitarian consequences of a nuclear attack by a Trident submarine on Moscow. Scottish CND. Link: https://www.banthebomb.org/images/stories/pdfs/ifbritainfiredtrident.pdf

Ainslie's detailed report reviews the UK's nuclear policy for its Trident nuclear weapons systems that was established in the early 1980s to target 'Soviet centres of power' in and around Moscow. He shows that attacking key military and political targets in and around Moscow with 40 nuclear warheads, then the stated complement on the single UK Trident submarine at sea, would result in 5.4 million deaths, 4.5 million inside the city and a further 870,000 in Moscow Region. This is an estimate of casualties within the first few months and does not take account of long-term effects.

FEEDING THE WORLD
IN A NUCLEAR WINTER

2.3 Feeding the world in a nuclear winter

A number of studies have examined ways in which the global population could be fed by developing and scaling production of 'alternative foods' following extreme catastrophes that could obscure the sun, including asteroid/comet impact, supervolcanic eruption, and nuclear war that causes a nuclear winter. Many of these studies have been led by Dr David Deckenberger (University of Canterbury, UK).[1]

A second set of studies has examined the processes by which humanity might survive a nuclear winter with a focus on Aotearoa New Zealand due to the effects of nuclear winter being less pronounced in the far Southern Hemisphere together with other social and geographic advantages.

Alternative foods

Denkenberger, D., Cole, D., Abdelkhaliq, M., Griswold, M., Hundley, A., & Pearce, J. (2017). Feeding everyone if the sun is obscured and industry is disabled. *International Journal of Disaster Risk Reduction*. 21, 284-290.
Link: https://doi.org/10.1016/j.ijdrr.2016.12.018

Blocking of the sun would result in the collapse of traditional agriculture and demand a new source of calories for the world's population. The reduced output of conventional agriculture would present a threat of causing mass starvation. This study showed that one solution in the short term is extracting edible calories from killed leaves using distributed mechanical processes. Then a constrained food web could be formed where part of the remainder from this could be fed to chickens, and the rest coupled with leaf litter could have mushrooms grown on it. A second group of solutions is growing mushrooms on dead trees and the residue going to cellulose digesting animals, such as cattle and rabbits. Typically, in these catastrophes the sun is not blocked completely, so some agriculture would be possible based on existing farming practices in extreme environments (e.g. growing UV and cold tolerant crops in the tropics). Furthermore, the cooling climate would cool the upper layer of the ocean, causing upwelling of nutrient-rich deep ocean water. This would facilitate algae growth in the ocean, feeding fish; retrofitting of ships to be sail-powered could enable significant fishing. The results of this study show these solutions could enable the feeding of everyone given sufficient preparation.

1 For an overview, see Baum, S., Denkenberger, D., & Pearce. J. (2016). Alternative Foods as a Solution to Global Food Supply Catastrophes. Solutions. 7: 4, 31-35.
Link: https://hal.science/hal-02113500/document

Denkenberger, D., & Pearce, J. (2015), Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun. *Futures*. 72, 57-68.
Link: https://doi.org/10.1016/j.futures.2014.11.008

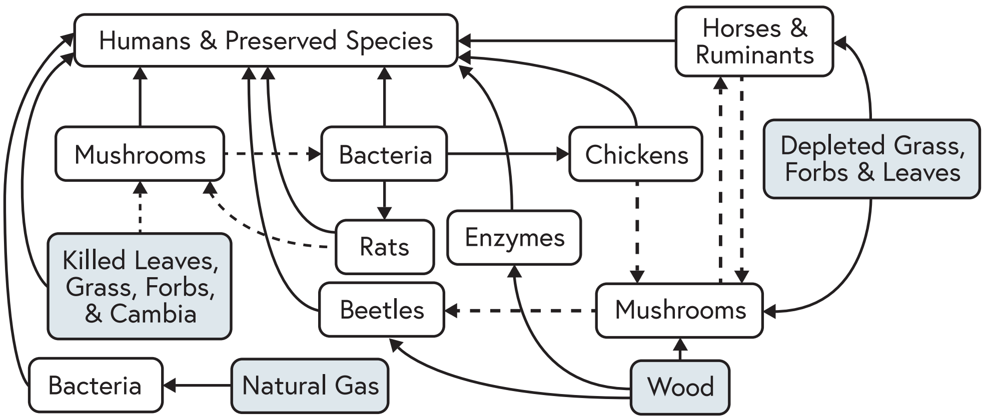
In this study, the researchers investigate the challenge of supplying five years of all humanity's caloric requirements in a global sun-blocking catastrophe by converting existing vegetation and fossil fuels to edible food products. Historically, storing food has been the only solution for a global loss of food supply. In this paper, the authors propose seven independent routes, ten promising options, and about 30 total options for providing the food necessary to support the entire human population. The seven promising routes to meet human food energy demands are: natural light (fishing); methane-digesting bacteria; enzyme-produced food; extracting food from thin biomass and then mushroom and cellulose digester conversion; thin biomass converted to bacteria; thick biomass (trees) converted to bacteria; and trees converted to mushrooms, cellulose-digesting beetles, rats, and/or chickens. These routes to produce 'alternative foods' do not require sunlight but use different energy sources. Alternative foods are already in limited production and could be scaled up following a major catastrophe.

Martínez, J., Egbejimba, J., Throup, J., Matassa, S., Pearce, J. & Denkenberger, D. (2021). Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios. *Sustainable Production and Consumption*. 25, 234-247.
Link: https://doi.org/10.1016/j.spc.2020.08.011

This study examines the production of microbial food from single cell protein (SCP) via hydrogen as alternative food for the most severe food shock scenario of a sun-blocking catastrophe, such as a nuclear winter. Multiple feedstocks can be used for SCP production, ranging from human edible products, such as sugar, to waste products including resources recovered from wastewater. The researchers show that this method could provide a portion of the population's protein requirements in addition to other alternative foods.

Baum, S.D., Denkenberger, D.C., Pearce, J.M., Robock, A. & Winkler, R. (2015). Resilience to global food supply catastrophes. *Environmental Systems and Decisions*. 35, 301–313 **Link:** https://doi.org/10.1007/s10669-015-9549-2

This study examines three options for food supply resilience in a global food supply catastrophe that cannot be addressed with food aid from external locations: food stockpiles, agriculture, and foods produced from alternative (non-sunlight) energy sources including biomass and fossil fuels. They find that agriculture can remain partially viable during some global food supply catastrophes, but it would not be enough to prevent massive food insecurity. Furthermore, the disruption to agriculture could last for many years. Stockpiles are versatile but expensive and current food stockpiles offer less than one year of food. Alternative food processes are not already in large-scale production and would need to be scaled up quickly to meet post-catastrophe food demand. How quickly alternative foods would need to be scaled up depends on how severely agriculture is disrupted and how much food has been stockpiled. Alternative foods may also face issues of social acceptability and face challenges in scaling up, given that alternative foods are a new and untested concept. They find that agriculture should in general be used as the first option, alternative foods as the second option, and food stockpiles as the third option. However, food supply resilience requires not just the food itself, but also the accompanying systems of food production and distribution, which would be at risk in global food catastrophe scenarios.



Select food sources and energy flows for alternative foods. Cambia are inner barks and forbs are nonwoody, non-grass plants. Solid lines are food. Dotted lines are waste. Shaded blocks are source resources

Surviving nuclear winter: Aotearoa New Zealand

Boyd, M., & Wilson, N. (2022). Island refuges for surviving nuclear winter and other abrupt sunlight-reducing catastrophes. *Risk Analysis*. 1– 19.
Link: https://doi.org/10.1111/risa.14072

The researchers examine the extent to which some island nations in the Southern Hemisphere might survive a severe sun-reducing catastrophe such as nuclear winter, and be well placed to help restart a collapsed human civilisation. They test the hypothesis that these island nations would typically suffer less from a nuclear winter and that complex technological society on such islands might persist and increase the probability of a global recovery. The researchers find that eight island nations meet a 'food self-sufficiency' threshold in the scenario of an India-Pakistan conflict in which each state detonates 50 15-kilotons nuclear weapons, causing firestorms that inject 5 teragrams of black soot into the upper atmosphere. These are Australia, Aotearoa New Zealand, Iceland, the Solomon Islands, Vanuatu, Indonesia, Mauritius and the Philippines. Amongst these, Australia, Aotearoa New Zealand, Iceland, the Solomon Islands, and Vanuatu should be able to produce enough food for their populations even during a very severe nuclear winter based on a US-Russia war that injects 150 teragrams of soot into the upper atmosphere.

The researchers then conduct a case study of Aotearoa New Zealand because it exhibits additional resilience factors. They posit that despite Aotearoa New Zealand's food production surplus, severe physical damage to northern hemisphere infrastructure (including ports, airports, energy, digital, and communications infrastructure), the effects of an electromagnetic pulse (EMP) generated by nuclear detonations (resulting for example from an attack on Australia), and possibly catastrophic near-100% crop failures in Europe and North America might lead to hoarding, internal conflict, and an inability to trade. They find that Aotearoa New Zealand could experience catastrophic limitations in transportation (including inter-island shipping), lack of fuel, or irreparable damage to infrastructure for growing, harvesting, processing, packaging, transport, and refrigeration of food. Such failures would have devastating cascading impacts across almost all sectors impeding coordination and distribution, possibly in the context of food rationing, hyperinflation, or price collapse. Energy disruptions could hinder manufacturing and lead to a breakdown of communication systems. Lack of clearly communicated information about risks, contingencies, plans, or rationing could contribute to social destabilisation. Fear of scarcity, combined with psychological trauma, could see an exodus from urban areas, absenteeism, and further degrading societal functioning.

They conclude that human extinction is unlikely to result from even a severe nuclear winter given the ability of societies on some island nations to continue. However, they identify a series of factors that suggest societies might survive, but not thrive, and even if societies manage to thrive at a local level, re-establishing a global technological civilisation from this foundation will be very difficult. They find that scenarios of no or low trade, precarious energy supply, shortcomings in manufacturing of essential components, inadequate preparations and critical failures in these systems could lead to rapid societal breakdown.

Green. W. (2022). Nuclear War: Are we prepared? Discussion Paper 2022/03. McGuinness Institute. **Link:** www.mcguinnessinstitute.org/publications/discussion-papers

The report is an update of a 1987 report by Wren Green, Tony Cairns and Judith Wright on 'New Zealand after Nuclear War' published by the New Zealand Planning Council. The study is based on a northern hemisphere nuclear war that has little radiological impact on the Aotearoa New Zealand population. However, it finds that:

- Abrupt loss of northern hemisphere trade would have immediate and long-term devastating impacts throughout all sectors of the economy given overwhelming reliance on imports. In the 1987 study, estimates suggested the loss of northern import and export markets could have immediately reduced employment by 40–50%. In addition, this would quickly spill over into the financial sector, affecting banks and the stock market, disrupting prices as assets and goods changed value overnight.
- Loss of trade would cripple health care. As people's health declined and medicines ran out, infectious and chronic diseases would spread and new ones such as plague and cholera could arrive later with refugees. Hospital functions would be steadily run down, intensive care facilities would cease and only a limited range of conditions could be operated on.
- A collapse of the health system and spread of lethal diseases would further weaken the social structure and reduce the resilience of communities. However, New Zealand's expanded pharmaceutical industry might develop the capacity to produce enough of the medicines on the World Health Organization's (WHO's) list of essential medicines to meet national needs after existing supplies ran out.
- The country has a near-total reliance on imports for all fuels (diesel, petrol, aviation). Onshore fuel stocks that would be available in the case of a major disruption are much lower than in most European countries with the government required to hold minimum levels of only 28, 24 and 21 days' worth of petrol, jet fuel and diesel respectively.
- Agriculture would be massively disrupted through the loss of export markets for livestock, imported seeds for many vegetables, fertilisers, trace elements, animal antibiotics, pesticides, herbicides and fungicides. Strict vaccination programmes would degrade and likely lead to cross-infection of people from animal diseases, such as leptospirosis, tetanus, tuberculosis and others. Overriding all these issues would be the availability of fuel to run farm machinery and rural transport, which, at present, is still mostly diesel.
- If fuel is scarce, food supplies to cities from farms and food processors could become erratic – assuming essential workers turn up for work and normal commerce functions in the chaos of the first days and weeks. There could be an unplanned (possibly chaotic) migration to rural areas from cities as jobs were lost and food scarcity became serious.
- Failure of the complex, interlinked system of global communications, cloud-computing and data storage would most likely happen as a consequence of a nuclear attack in the US in the first instance, and would have very significant effects on the ability of New Zealand's society to function without electronic information, payments and communications.

Wilson, N., Payne, B. & Boyd, M. (2023). Mathematical optimization of frost resistant crop production to ensure food supply during a nuclear winter catastrophe. *Nature: Scientific Reports.* 13: 8254. Link: https://doi.org/10.1038/s41598-023-35354-7

See also Wilson, N., Prickett, M., & Boyd, M. (2023). Food security during nuclear winter: A preliminary agricultural sector analysis for Aotearoa New Zealand. *The New Zealand Medical Journal (Online)*. 136: 1574, 65-81.

Link: https://www.proquest.com/scholarly-journals/food-security-during-nuclear-winter-preliminary/docview/2809560267/se-2

The researchers estimate the optimal mix of frost resistant crops and land area needed to provide basic nutrition during various nuclear winter scenarios for Aotearoa New Zealand as a temperate island state. The scenario is based on a major nuclear war that injects 150 teragrams of soot into the upper atmosphere. The study shows that at current production levels of frost resistant crops in Aotearoa New Zealand, there would be a 26% shortfall for the 'war without a nuclear winter' scenario and a 71% shortfall for the severe nuclear winter scenario based on a major nuclear war that injects 150 teragrams of soot into the upper atmosphere leading to a 61% decline in crop yields.

However, in a scenario where it is assumed that half of all dietary energy and protein comes from other sources, feeding the population would be possible. In this scenario, current levels of frost resistant crop production could provide an excess of dietary energy in all scenarios except for a shortfall in the severe nuclear winter scenario (i.e., with only 58.5% of the needed production occurring).

The study finds that the optimised combination of frost resistant crops in the modelling was a combination of wheat (97% of the required cropping area) and carrots for the remainder. Wheat is already grown in Aotearoa New Zealand, including at world-leading yield levels, but production is dependent on imported diesel, fertiliser and pesticides. However, the authors note that Aotearoa New Zealand will be vulnerable to various levels of socio-economic collapse after a nuclear war, which could seriously disrupt food production, transport, processing and retailing and a financial system collapse could limit citizens from being able to purchase food.

THE EFFECTS OF AND RESPONSES TO A 10-KILOTON NUCLEAR DETONATION

2.4 The effects of and responses to a 10-kiloton nuclear detonation

After the terrorist attacks of 11 September 2001, many states began to focus on the risk of nuclear terrorism. In the US, the Department of Homeland Security was mandated to develop national emergency response plans centred on 15 National Planning Scenarios. The first of these was the detonation of a 10 kiloton (kt) 'improvised nuclear device' (IND) in a large metropolitan area. This prompted a new wave of scholarship that looked at how the medical community would be able to deal with victims, how the population of a city would react, and the impacts of destruction and disruption of critical infrastructure and mass displacement of people.

These studies show that it would be extremely difficult for the federal government to provide assistance within the first 24 hours and that very little could be done to help those in the innermost zone of destruction and prompt radiation. Moreover, the costs of the decontamination and rebuilding would be enormous and the long-term impacts on society would be massive.

(2005) National Planning Scenarios: Created for Use in National, Federal, State, and Local Homeland Security Preparedness Activities.
Link: https://info.publicintelligence.net/national_planning_scenarios.pdf

The 2005 version of the National Planning Scenarios states that whilst it is extremely difficult to estimate the true implications of terrorist use of a nuclear device on a US city, the health consequences to the population directly impacted would be severe, the physical damage to the community would be extreme, and the costs of the decontamination and rebuilding would be staggering. More specifically, the document says:

- There will be hundreds of thousands of casualties, up to 3000 square miles could be contaminated with radiation, the economic impact will be in the hundreds of billions of dollars, and recovery will take years.
- The detonation of an IND in a US city would forever change the American psyche as well as its politics and worldview.
- The detonation will cause many secondary hazards, including damaged buildings, downed power and phone lines, leaking gas lines, broken water mains, weakened bridges and tunnels and significant releases of hazardous materials.
- The electromagnetic pulse (EMP) produced by the blast has the potential to disrupt the communication network, other electronic equipment, and associated systems within approximately a 5-kilometre range. The infrastructure of the electrical power grid, mobile phone towers, broadcasting stations, computer networks, switching stations and so on are vulnerable to EMP.

- There likely will be significant damage to the general public support infrastructure with potentially cascading effects. These systems include transportation lines and nodes (e.g., air, water, rail, highway); power generation and distribution systems; communications systems; food distribution; and fuel storage and distribution. There will be concerns about the safety and reliability of many structures (e.g., dams, levees, nuclear power plants, hazardous material storage facilities). Structures may be damaged that are used to provide essential services (e.g., hospitals and schools).
- All people, including the emergency response workers, entering the high radiation areas near the blast site, have a significant probability of receiving large (likely fatal) radiation doses. By far, the most dangerously radioactive fallout will be deposited near the detonation site and will happen within the first couple of hours after detonation but may expose many people to large doses and will certainly contaminate large areas of land for years. Many fatalities and injuries will result from a combination of these various effects.
- Years later, there will still be health consequences in the form of increased probabilities of cancers in the exposed population. The number of these cancers will likely run into the thousands and will extract a large human, social, and financial cost.
- It is likely that the blast and subsequent fires will destroy all buildings in the immediate area of the detonation. Historically, decontamination of sites involves the removal of all affected material. Often, this includes the surface of the ground to a depth of several inches over the entire area that has been contaminated. Therefore, most buildings in the immediate downwind fallout path will likely have to be destroyed in the decontamination effort. At some distance, the buildings will not have to be destroyed and removed but will still require decontamination of all affected surfaces. This decontamination process will take years and will be extremely expensive. The decontamination will produce a far greater challenge and cost much more than the actual rebuilding of the destroyed structures.
- The national economy will be significantly impacted. Decontamination, disposal, and replacement of lost infrastructure will cost many billions of dollars. Replacement of lost private property and goods could add billions more to the cost. Additionally, an overall national economic downturn, if not recession, is probable in the wake of the attack.

Parikh, N., Hayatnagarkar, H.G., Beckman, R.J. et al. (2016). A comparison of multiple behavior models in a simulation of the aftermath of an improvised nuclear detonation. *Autonomous Agents and Multi-Agent Systems*. 30, 1148–1174.
Link: https://doi.org/10.1007/s10458-016-9331-y

These researchers ran simulations within a highly developed synthetic representation of the National Capital Region that includes Washington, D.C., the urban built infrastructure and a synthetic population based on census data in which each synthetic individual is capable of making a range of choices in response to the detonation of a 10kt IND based on how people respond to disasters. The research shows that modelling human behaviour gives a more accurate - and lower - estimate and deaths and casualties based on the static population alone, but not by much. In this scenario, the baseline death toll after 48 hours was 279,000, predominantly from radiation exposure. Modelling human behaviour in response to the detonation reduces the death toll by about 2,000 based on a range of possible behaviours, such as evacuation, shelter, seeking first aid, finding family members and so on. The research suggests that *there is little that can be done* in terms of incentivising particular behaviours by a population to meaningfully reduce the death toll in this scenario.

Coleman, C., Knebel, A., Hick, J., et al. (2011). Scarce Resources for Nuclear Detonation: Project Overview and Challenges. *Disaster Medicine and Public Health Preparedness.* 5: S1. Link: https://doi.org/10.1001/dmp.2011.15

In 2011, a set of articles was published in a special issue of *Disaster Medicine and Public Health Preparedness* based on a panel convened by the US Assistant Secretary for Preparedness and Response (ASPR) in the US Department of Health and Human Services to plan how to respond to a 10kt IND detonation in a US city. Coleman et al look at the effects on healthcare systems in Washington, D.C. They show that local healthcare resources will be completely overwhelmed by demand. Based on computer modelling, approximately 1,000 beds are vacant within the Washington, D.C. metropolitan area, compared with a predicted need for 180,000 beds following a 10kt detonation. For paediatric patients, the number of vacant beds is closer to 250 and estimates for critical care beds are even lower. With fewer than 100 ambulances serving Washington, D.C. and emergency responder operations limited by high levels of radioactive and infrastructure damage, the most severely injured patients with or without radiation injury will not receive life-sustaining medical care quickly, and many will die from their injuries. Resource scarcity at local medical care sites will improve with time after the detonation, but they may not reach normal levels for an extended period. Hospitals and referral centres some distance from the detonation might not be affected for several days, after which they will likely face shortages or be overwhelmed as casualties arrive or supplies cannot be replenished due to intense demand.

Support for patients suffering severe Acute Radiation Syndrome (ARS) and other injuries will be very difficult because treatment is highly labour- and resource-intensive. For example, the authors cite a single casualty of the Tokaimura radiation accident in Japan in 1999 who “required abundant personnel and resources for comprehensive and intensive care, including approximately 10 litres of fluid daily and extensive transfusion support.” Such support would not be possible for the number of ARS patients expected after a 10kt detonation. Moreover, only a small fraction of US health care practitioners have either training or experience in the field of radiation injury. The authors note that “Despite more than 6 decades of research, major gaps exist in our understanding of how genetic, demographic, geographic, and other factors would affect radiation injuries after a nuclear detonation in a modern US city."

However, casualties can be reduced through careful planning to best allocate scarce healthcare resources: specific processes for triaging patients after a nuclear detonation are not well understood; there is insufficient familiarity with radiation injury and its treatment; laboratory capacity for biodosimetry (used to assess the radiation dose a person received) is insufficient; and there is insufficient understanding of the effects of a nuclear detonation on medical systems overall.

Hick, J., Weinstock, D., Coleman, C., et al. (2011). Health Care System Planning for and Response to a Nuclear Detonation. *Disaster Medicine and Public Health Preparedness*. 5: S1, S73-S88. Link: https://doi.org/10.1001/dmp.2011.28

The authors of this paper look at the likely long-term health consequences. They show that many victims in the 10 kt IND scenario will have extraordinary social and behavioural health support requirements. Children will be particularly vulnerable to severe and long-term mental health and behavioural consequences. In addition, their families, providers, and the community at large will experience long-term psychological effects. Patients with pre-existing psychiatric illness will be extremely destabilised by the incident and will have increased care requirements. Displacement and behavioural health issues are not rapidly resolved. Six years after Hurricane Katrina struck New Orleans in 2005, two-thirds of displaced children exhibit emotional or behavioural problems and half remain in temporary housing.

Within the first few years after the incident, blood cancers (myelodysplastic syndromes) may develop, with radiation-induced solid tumours occurring many years or decades later, in a subset of exposed people. They show that the recovery phase of a nuclear incident is exceptionally prolonged in relation to other catastrophic incidents that do not require lifetime surveillance and ongoing care. No other disaster will affect the lives of the victims, their families, and providers as profoundly.

Burkle F. and Dallas C. (2016). Developing a nuclear Global Health workforce amid the increasing threat of a nuclear crisis. *Disaster Medicine and Public Health Preparedness*. 10: 1:129–44. Link: https://pubmed.ncbi.nlm.nih.gov/26527407/

The authors of this paper show that life-saving opportunities are possible after a 10kt IND detonation, but only if a rapidly deployable, robust professional workforce required for large-scale nuclear crises exists, which it currently does not. They propose a framework for developing a nuclear global health workforce, recognising that "a nuclear event anywhere is a nuclear event everywhere". This will require the establishment of nuclear triage centres, nuclear survival centres, nuclear palliative care centres, and health system support centres.

They show that the current nuclear response organisations, such as the World Health Organisation's (WHO) Radiation Emergency Medical Preparedness and Assistance Network (REMPAN), are very limited and will find themselves beset with similar, but even more grievous, challenges after a nuclear detonation than those that confronted responders during the rapidly spreading Ebola epidemic in 2014 to 2016. They highlight the following major public health challenges in responding to nuclear events:

1. Limited capacity and availability of radiation health experts for monitoring potentially exposed people for radioactive contamination.
2. Limited mobilisation, recruitment, training, and valid exercises of the very large numbers of medical and public health personnel required for nuclear event response, especially for nuclear weapon use.
3. Lack of the utility, training, and understanding of the feasibility of radiation decontamination among health care facilities and health responders.
4. No public health authority to detain people contaminated with radioactive materials.
5. Limited public health and medical capacities for a coordinated medical response to nuclear weapon detonations.
6. Insufficient public health communications and response for the unique aspects of radiation-related mass events.
7. Limited access to timely radiation emergency monitoring data.
8. Insufficient distribution potential for potassium iodide (KI) in response to airborne radioiodine to meet the narrow window of effective distribution (no later than four hours after exposure).
9. Lack of timely access (or knowledge) concerning highly effective approved and experimental radio-protectant drugs.
10. Lack of knowledge and training with approved and stockpiled thermal burn treatments ideal for mass casualty burn applications.
11. Lack of knowledge of rapid questionnaire for radiation exposure triage generated from the experience of highly exposed Chernobyl workers.
12. Lack of knowledge of health care workers for environmental radiation effects versus medical radiation use, myths and realities of radiation exposure.

They conclude that the healthcare response will be totally inadequate to address the health outcomes for an urban nuclear detonation resulting from trauma, thermal burn, and radiation and the very large number of victims, in part due to the lack of familiarity with victims of environmental radioactivity in the medical experience of virtually all healthcare providers. It is highly unlikely that the thousands of burn victims after an IND detonation will receive *any* meaningful medical treatment given the high degree of effort currently necessary in emergency thermal burn care. Even with the unlikely scenario that health facilities remain intact and all health care workers survive and respond, existing health care systems will not have the capacity to deal with the catastrophic number of victims. The authors estimate that at best, there will be over 1,000 critical victims for each surviving physician.

Veenema, T.G., Burkle, F.M. & Dallas, C.E. (2019). The nursing profession: a critical component of the growing need for a nuclear global health workforce. ***Conflict and Health*** **13, 9. Link:** https://doi.org/10.1186/s13031-019-0197-x

The authors highlight the central role of nurses in responding to a 10kt IND detonation scenario. They highlight problems in the US with a steady decrease in training for burn treatment nurses given the number of thermal burn cases expected with any nuclear weapon use, and the fact that few US nurses have either training or experience in the field of radiation injury. They highlight the challenges of rapidly establishing fixed and mobile health care facilities to meet the massive surge in demand for care, specifically initial triage and dose-monitoring, assessment, decontamination, and patient transfer.

The authors also highlight the challenges of managing the psychological, emotional and behavioural effects of a nuclear detonation. They conclude that these

> "are certain to be of staggering proportions, rippling through communities both near and far. Depression, anxiety, acute and post-traumatic stress disorder, poor self-reported health status and medically unexplained somatic symptoms characterise the psychological impact of large-scale radiation events. The lifetime prevalence of depression in women 11 years after Chernobyl was double the lifetime prevalence in women in the Ukraine. Fear of developing cancer may be long-lasting and perpetuate negative mental health impacts, leading to self-medication through the increased use of alcohol and pharmaceuticals, and an increase in family disintegration and violent/antisocial behavior. Social decay and civil unrest may occur."

Medical impact of other nuclear detonation scenarios

Cham Dallas (Professor of health policy and management in the College of Public Health, University of Georgia and the Director of the Institute for Disaster Management) has also examined scenarios for nuclear detonations of much larger yield in the US and in a hypothetical Iran-Israel nuclear war.

Dallas, C. and Bell, W. (2007). Prediction modelling to determine the adequacy of medical response to urban nuclear attack. ***Disaster Medicine and Public Health Preparedness*****, vol. 1: 2. Link:** https://doi.org/10.1097/DMP.0b013e318159a9e3

The authors model the effects of 20 and 550kt nuclear detonations on the two major metropolitan centres of Los Angeles and Houston with a focus on burn victims ('thermal casualties'). They report that the thermal casualties that *survived* the 550kt detonation are estimated at 185,000 and 59,000 for Los Angeles and Houston respectively, and 28,000 and 10,000 people for the 20kt detonation. They observe that the surviving healthcare community would be faced with an unprecedented burden of care for burn casualties. This burden would be compounded by the loss of physical (e.g., hospitals, clinics) and human resources as demonstrated by their modelling results.

Bell, W. and Dallas, C. (2007). Vulnerability of populations and the urban health care systems to nuclear weapon attack—examples from four American cities. *International Journal of Health Geographics*. 6: 5.

Link: https://ij-healthgeographics.biomedcentral.com/articles/10.1186/1476-072X-6-5

In this paper, the authors examine the effect of 20kt and 550kt nuclear detonations on New York City, Chicago, Washington, D.C. and Atlanta. They use models developed by the US Defense Threat Reduction Agency (DTRA) for calculating mass casualties from a nuclear detonation. In the 550kt scenario, the destruction of the major hospitals in the downtown areas is nearly complete in all four cities. In New York City, 51% of hospitals and 53% of the medical staff are lost within 20 miles of ground zero in Manhattan. The loss of Washington, D.C. health care systems from the thermal and blast effects and the loss of Baltimore hospitals from the fallout plume 40 miles away is significant: a 48% loss of hospitals in the 20 mile buffer around the two cities, a 57% loss of beds, and 67,000 health care workers directly affected for a total loss of 62% of the workers. The authors demonstrate that a staggering number of the main hospitals, trauma centres, and other medical assets are likely to be in the fatality radiation plume, rendering them essentially inoperable in a crisis in both the 550kt and to a lesser extent the 20kt scenarios. The authors emphasise that there are very few burn beds in the entire US (< 1,500) and only a few (less than 150) are not occupied at any one time. Even a small nuclear event will totally overwhelm the ability to take care of resulting burn casualties.

Dallas, C. et al. (2013). Nuclear war between Israel and Iran: lethality beyond the pale. *Conflict and Health*. 7: 10.

Link: https://conflictandhealth.biomedcentral.com/articles/10.1186/1752-1505-7-10

The authors use established models to examine the blast, thermal and radiation effects of a war between Iran and Israel involving nuclear detonations on three Israeli and eighteen Iranian cities. They show that this will result in millions of dead, with millions of injured suffering without adequate medical care, a broad base of lingering mental health issues, a devastating loss of municipal infrastructure, long-term disruption of economic, educational, and other essential social activity, and a breakdown in law and order. Based on a detailed analysis of Iranian and Israeli nuclear capability by the Center for Strategic and International Studies, the authors assume a hypothetical Israeli nuclear arsenal of at least 200 boosted and fusion weapons, with yields from 20kt to 1 mt. Iran is assumed to have an arsenal of 10 to 20 nuclear weapons, mostly fission devices, in the range of 15 to 30kt. For Israel, a 15kt nuclear weapon was simulated. For Iran, five sizes of nuclear weapons of 15, 50, 100, 250 and 500kt were employed in single and multiple strikes on cities. The authors note that particularly the lack of urban sprawl means concentrated population density in Iranian cities, which multiplies vulnerability to nuclear attack. Detailed tables of estimated direct and indirect deaths for each scenario are provided in the article.

Boulton, F. (2013). Blood Transfusion Services in the wake of the humanitarian and health crisis following multiple detonations of nuclear weapons. *Medact*, London. **Link:** https://www.medact.org/wp-content/uploads/2014/01/report-bloodtransfusionnuclearweapons-jan2013.pdf

Related to the above studies, retired UK physician and haematologist Frank Boulton, who latterly specialised in blood transfusion, shows that the detonation of a single 100kt nuclear warhead (the estimated yield of the UK Trident warhead) above a major UK city would rapidly overwhelm healthcare services and clinical demand for intravenous fluids, plasma, whole blood, clotting factors and so on. He notes that there are usually only approximately a dozen burn beds for adults and a similar number for children in each UK region (around 600 beds in the whole UK at any one time, many of which are occupied). The national supply of burns beds would be overwhelmed as would the blood supply system to respond to the scale of injuries requiring blood products. For transfusion, even if people further away responded by giving blood, the capacity for collecting, processing and testing would be compromised, as would storage, refrigeration, record-keeping (particularly if paperwork had to replace computerised records) and indeed hospital capacity and available medical personnel. Moreover, “any attempts at triage would be largely ineffective, complicated further as it would be by major hospital destruction and vastly reduced bed availability, if not complete loss”.