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Opinion

Opinion: How fear of nuclear winter has helped save the world, so far

Alan Robock[1], Lili Xia[1], Cheryl S. Harrison[2], Joshua Coupe[5,a], Owen B. Toon[3], and Charles G. Bardeen[4]

[1]Department of Environmental Sciences, Rutgers University, 14 College Farm Road, New Brunswick, New Jersey 08901, USA
[2]Department of Ocean and Coastal Science and Center for Computation and Technology, Louisiana State University, Baton Rouge, Louisiana 70803, USA
[3]Department of Atmospheric and Oceanic Sciences, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80303, USA
[4]Atmospheric Chemistry Observations and Modeling Laboratory, National Center for Atmospheric Research, Boulder, Colorado 80307, USA
[5]Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado 80309, USA
[a]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado 80309, USA

Correspondence: Alan Robock (robock@envsci.rutgers.edu)

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Abstract. The direct effects of nuclear war would be horrific, with blasts, fires, and radiation killing and injuring many people. But in 1983, United States and Soviet Union scientists showed that a nuclear war could also produce a nuclear winter, with catastrophic consequences for global food supplies for people far removed from the conflict. Smoke from fires ignited by nuclear weapons exploded on cities and industrial targets would block out sunlight, causing dark, cold, and dry surface conditions, producing a nuclear winter, with surface temperatures below freezing even in summer for years. Nuclear winter theory helped to end the nuclear arms race in the 1980s and helped to produce the Treaty on the Prohibition of Nuclear Weapons in 2017, for which the International Campaign to Abolish Nuclear Weapons received the 2017 Nobel Peace Prize. Because awareness of nuclear winter is now widespread, nuclear nations have so far not used nuclear weapons. But the mere existence of nuclear weapons means that they can be used, by unstable leaders, accidently from technical malfunctions, such as in computers and sensors, due to human error, or by terrorists. Because they cannot be used without the danger of escalation (resulting in a global humanitarian catastrophe), because of recent threats to use them by Russia, and because nuclear deterrence doctrines of all nuclear-armed states are based on the capability and readiness to use nuclear weapons, it is even more urgent for scientists to study these issues, to broadly communicate their results, and to work for the elimination of nuclear weapons.

Dedication. This article is dedicated to Paul Crutzen (1933–2021). Along with John Birks, he pointed out that nuclear war would produce massive smoke clouds, which led directly to nuclear winter theory.

1 History of nuclear winter theory

Crutzen and Birks (1982) were the first to point out that a nuclear war could ignite extensive forest fires, producing dark smoke in the troposphere, but they did not comment on whether the smoke would produce a net cooling or warming at the surface. However, Turco et al. (1983) understood that cities and industrial areas targeted by nuclear weapons would generate even more smoke than forests and that the soot would rise into the stratosphere. The smoke would spread over the entire Earth and produce global climate change so large that the climatic impacts were described as "nuclear winter." While Turco et al. (1983) used a one-dimensional radiative-convective model, Aleksandrov and Stenchikov (1983) were the first to use a three-dimensional general circulation model (GCM), and they also found that there would be nuclear winter over the land even though the model included the effects of oceans. This new research showed that there could be global impacts of nuclear war far from the target areas and nations involved in the war. While the direct effects of a nuclear war might kill hundreds of millions in combat zones, the indirect effects could lead to collapse of world agriculture and starvation of billions of people even in regions that were not involved directly in the war.

The basic science of nuclear winter is not complicated. If nuclear weapons were exploded on cities and industrial areas, probable targets of nations with those weapons, they would start fires, producing massive amounts of smoke, some of which would end up in the stratosphere. That smoke would block out sunlight, making it cold, dark, and dry at the surface for many years, as well as heat the stratosphere, destroying ozone and producing enhanced ultraviolet radiation at the surface after a sufficient amount of smoke had cleared. The magnitude of the impacts would depend on the number and yield of the nuclear weapons used, as well as the specific targets.

The early nuclear winter simulations were limited by the climate models and computing power available for the calculations. But the basic science seemed settled, as summarized by Pittock et al. (1986), Turco et al. (1990), and Sagan and Turco (1990). We know of no new climate modeling done on this topic until the past 20 years, since the *Atmospheric Chemistry and Physics* journal was founded. Each of the previous simulations addressed certain aspects of the climate model response with simple climate models or with short simulations of low-resolution atmospheric GCMs.

Aleksandrov and Stenchikov (1983) used a very-low-resolution ($12° \times 15°$ lat–long) atmospheric GCM with only 2 levels in the vertical coupled to a mixed-layer ocean and annual average solar radiation, and they conducted one 400 d simulation. They forced the model with 150 Tg of smoke, the amount that would have been generated by about 1/3 of the US and Soviet nuclear arsenal at the time. Their simulation produced surface temperature changes to values far below freezing and an overturning atmospheric circulation cell transporting the aerosols globally. MacCracken (1983) used a similar model and produced similar results.

Turco et al. (1983) gave the name "nuclear winter" to this work, capturing the forcing and response in a two-word phrase. Their single column model was intended to simulate mid-continent conditions as it had no surface heat capacity. They used many different scenarios and simulated the detailed vertical patterns of climate response but were not able to look at dynamical responses or the spatial distribution of climate change.

In the next couple of years, the primitive, by today's standards, National Center for Atmospheric Research atmospheric GCM was used by Covey et al. (1984) and Thompson (1985) for short runs at different times of the year, validating the earlier GCM results of Aleksandrov and Stenchikov (1983) and MacCracken (1983). Robock (1984) was the first to study the entire seasonal cycle and interannual responses, using an energy-balance model with a mixed-layer ocean. He found that snow and sea ice albedo feedbacks prolonged the cooling even though he used the short atmospheric smoke lifetime from Turco et al. (1983). This result was later validated with GCM simulations using a mixed-layer ocean (Schneider and Thompson, 1988; Ghan, 1991). Malone et al. (1985) showed that lofting of aerosols in the summer due to solar heating would prolong their lifetime, because they would be in the stratosphere where they could not be removed by precipitation, but they used a model with a low top of the atmosphere (32 km) and were only able to run it for 40 d.

Ghan et al. (1988) and Pittock et al. (1989) investigated the impacts of different assumptions about smoke optical properties. The decade ended with Turco et al. (1990) summarizing the work since the original Turco et al. (1983) paper, and they showed that the conclusion that a nuclear winter could result from nuclear war was still robust. However, there were still details to be studied, and they outlined some important questions about the emissions of smoke, smoke properties, and climate response.

Another decade and a half passed before nuclear winter research got going again. Progress in computing and climate modeling allowed for investigations that previously were impossible. In the 1980s the fastest "supercomputers" were orders of magnitude slower and had orders of magnitude less storage than the smartphones most of us carry around in our pockets today. Thus, simulations had to ignore much of the physics and chemistry of the atmosphere, and they could not represent the full depth of the atmosphere or be run long enough to study the interannual response to a smoke injection. Robock et al. (2007a) conducted climate model simulations with a then state-of-the-art GCM, ModelE from the National Aeronautics and Space Administration Goddard Institute for Space Studies (Schmidt et al., 2006), which included a module to calculate the transport and removal of aerosol particles (Koch et al., 2006). The atmospheric model was connected to a full ocean general circulation model with calculated sea ice, thus allowing the ocean to respond quickly at the surface and on yearly timescales in the deeper ocean. Robock et al. (2007a) ran the atmospheric portion of the model at $4° \times 5°$ latitude–longitude resolution, with 23 vertical layers extending to a model top of 80 km. The coupled oceanic general circulation model (Russell et al., 1995) had 13 layers and also a $4° \times 5°$ latitude–longitude resolution. Simulations were run over a decade, not just a few weeks. This work extended the time and sophistication of climate model capabilities and showed a long timescale of climate response not possible with previous models. For the first time, we learned that smoke would stay in the stratosphere for multiple years as we could simulate the heating and lofting of the smoke, preventing it from quickly falling out of the air. The basic conclusion that a large-scale nuclear conflict would have devastating climatic consequences was not only supported but also strengthened.

Using simple scenarios of 50 and 150 Tg of soot injected into the upper troposphere, Robock et al. (2007a) found that indeed the 150 Tg scenario, with an injection of soot which is still possible from the use of the current US and Russian nuclear arsenals (Toon et al., 2008), would produce a nuclear winter. And they found that the climate effects would last for more than a decade, as for the first time they were able to realistically simulate the lifetime of the soot particles in the upper atmosphere. Coupe et al. (2019) repeated these experiments using the Community Earth System Model-Whole Atmosphere Community Climate Model version 4 (WACCM4; Marsh et al., 2013; Bardeen et al., 2017), run at $1.9^\circ \times 2.5^\circ$ horizontal resolution with 66 layers from the surface to 140 km, with full stratospheric chemistry and with the Community Aerosol and Radiation Model for Atmospheres in the stratosphere allowing particle growth (Toon et al., 1988; Turco et al., 1979; Bardeen et al., 2008, 2017). Remarkably, the Robock et al. (2007a) and Coupe et al. (2019) models produced similar results. Nuclear winter, with below-freezing temperatures over much of the Northern Hemisphere during summer, would occur due to a significant reduction of surface solar radiation due to smoke lofted into the stratosphere. The more sophisticated aerosol representation in WACCM4 removes this smoke more quickly, but the magnitude of the climate response is not reduced. In fact, the higher-resolution WACCM4 simulates larger temperature and precipitation reductions than ModelE in the first few years following a 150 Tg soot injection. A strengthening of the northern polar vortex is modeled during winter by both models in the first year, contributing to above-normal but still below freezing temperatures in the Arctic and northern Eurasia.

After the 6 August 1945 atomic bombing of Hiroshima and the 18 April 1906 San Francisco earthquake, large firestorms pumped smoke into the stratosphere, and current nuclear arsenals with much larger weapons would do the same when targeted on cities. Large pyrocumulonimbus following forest fires were observed recently to inject smoke into the stratosphere (e.g., Yu et al., 2019), and high-resolution modeling of city fires (Redfern et al., 2021), as part of our research, further supports the theory that stratospheric smoke injections occur.

2 Reagan and Gorbachev

In 1986 US President Ronald Reagan and General Secretary Mikhail Gorbachev of the Soviet Union took the first steps in history to reduce the numbers of nuclear weapons. When the first nuclear winter results were produced by American (Turco et al., 1983; MacCracken, 1983; Covey et al., 1984; Robock, 1984) and Russian (Aleksandrov and Stenchikov, 1983) scientists, they were accepted by President Reagan and General Secretary Gorbachev. When asked about the effects of nuclear war in a 12 February 1985 interview in the *New York Times* (Reagan, 1985), Reagan said,

> A great many reputable scientists are telling us that such a war could just end up in no victory for anyone because we would wipe out the earth as we know it. And if you think back to... natural calamities – back in the last century, in the 1800s,... volcanoes – we saw the weather so changed that there was snow in July in many temperate countries. And they called it the year in which there was no summer. Now if one volcano can do that, what are we talking about with the whole nuclear exchange, the nuclear winter that scientists have been talking about? It's possible.

Gorbachev said,

> Models made by Russian and American scientists showed that a nuclear war would result in a nuclear winter that would be extremely destructive to all life on Earth; the knowledge of that was a great stimulus to us, to people of honor and morality, to act in that situation (Hertsgaard, 2000).

By 1990 the arms race and Cold War had ended. Since then, the global nuclear arsenal has been reduced by a factor of more than six. We were proud to have had a role in this, and that science speaking truth to power had actually worked. Figure 1 shows the number of deployed nuclear weapons on Earth over time. The Soviet Union did not end until 1991, long after the arms race was over, so that is not what ended the nuclear arms race. But the total is still more than 12 000 nuclear weapons, with 4000 deployed, and all much larger than those used in the first nuclear war in 1945. They can still produce nuclear winter (Robock et al., 2007a; Coupe et al., 2019), so the problem is not yet solved.

3 India and Pakistan

There are now nine nuclear states. In addition to the USA and Russia, they are the United Kingdom, France, China, India, Pakistan, Israel, and North Korea. As the current century began, we went on to work on other issues, but as a low-grade war continued between India and Pakistan along the Line of Control in Kashmir, journalists still wondered about the consequences should one of these skirmishes escalate into a nuclear war. Brian Toon and Rich Turco led an effort to estimate how much smoke might be generated by such a war (Toon et al., 2007), and Robock et al. (2007b) used a modern climate model to calculate the resulting climate change. With an estimated 5 Tg of soot from 100 city attacks using 15 kt atomic bombs, the same size that destroyed

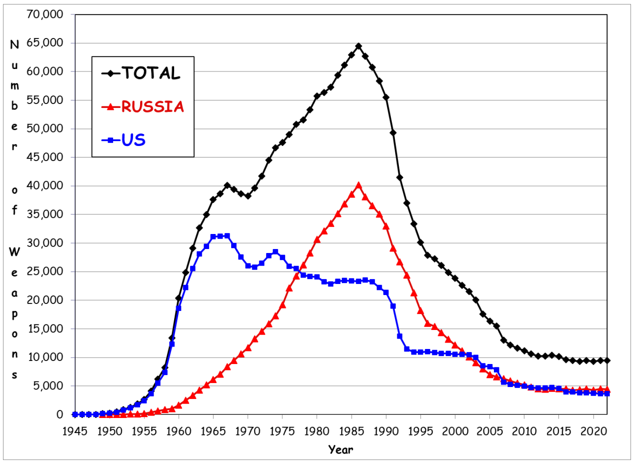

Figure 1. Time series of the total number of nuclear weapons on Earth, which after about 2005 excludes large numbers of tactical nuclear weapons as well as weapons in storage waiting to be dismantled. The total includes all nine nuclear-weapon states, but the other seven have at most a few hundred each (Kristensen and Norris, 2015), updated 2023 from Bulletin of the Atomic Scientists (2023).

Hiroshima on 6 August 1945, using the National Aeronautics and Space Administration/Goddard Institute for Space Studies ModelE GCM, they calculated global average cooling of more than 1 K, to a temperature colder than ever before experienced in recorded human history. This was the first time an atmosphere–ocean GCM had been used for this problem, and it was one that had a complete stratosphere and mesosphere, allowing calculation of the lofting of the smoke by solar heating and its global distribution. They calculated an *e*-folding lifetime for the smoke of 7 years, with a climate response lasting more than a decade. Subsequent simulations with other GCMs (Mills et al., 2014; Stenke et al., 2013; Pausata et al., 2016; Wagman et al., 2020) found very similar results.

For the first time, the world came to the realization that not only would a nuclear war between the two superpowers be a global catastrophe, but a war between any nuclear states using less than 1 % of the global arsenal would be similarly catastrophic. It would not be nuclear winter but could still have serious consequences for agriculture and the world food supply unmatched in modern history (Özdoğan et al., 2013; Xia and Robock, 2013; Xia et al., 2015).

4 Humanitarian impacts conferences

Alarmed by the continuing global threat of nuclear war, multiple activists from around the world organized themselves into the International Campaign to Abolish Nuclear Weapons (ICAN). ICAN (https://www.icanw.org/, last access: 12 June 2023) now has 650 partner organizations from 110 nations worldwide. To educate the world about the continuing threat of nuclear weapons, Norway, Mexico, and Austria organized three international conferences on the humanitarian impacts of nuclear war – in Oslo, Norway (2–3 March 2013); Nayarit, Mexico (13–14 February 2014); and Vienna, Austria (8–9 December 2014) – as governmental expert conferences. ICAN and other non-governmental organizations as well as academic experts were invited to participate. ICAN also organized separate civil society events in the margins of the three governmental conferences and campaigned for states to attend. In addition to testimony from hibakusha survivors of the Hiroshima and Nagasaki bombings in 1945, our work on the agricultural impacts was presented in Norway by Alan Robock and Ira Helfand, in Mexico by Alan Robock, and in Austria by Michael Mills.

Each of these conferences was attended by diplomatic representatives from over 100 nations. Many of them learned for the first time about the remote consequences for themselves of a nuclear war fought on the other side of Earth, even if no bombs were dropped on them. They were energized to do something about it.

5 Treaty on the Prohibition of Nuclear Weapons

In 2017, four countries, Austria, Ireland, Mexico, and South Africa, later expanded to include Brazil, Costa Rica, Indonesia, New Zealand, Nigeria, and Thailand, led a process to obtain a mandate in the United Nations General Assembly to negotiate a treaty to ban nuclear weapons. These states submitted resolutions in the General Assembly that garnered the necessary support to conduct the negotiations. ICAN successfully campaigned all along for states to support this activity, but it was a state-led process. At that time, nuclear weapons were the only weapons of mass destruction that were not banned. Chemical and biological weapons had been banned but not the most destructive of all. Spurred by what they had learned at the humanitarian conferences and activism by the ICAN partners in their nations and the International Committee of the Red Cross, 135 nations, as well as members of civil society, came to the UN General Assembly and negotiated in March, June, and July 2017. Alan Robock made a presentation there on "Climate effects of limited and large-scale nuclear war" on 27 June 2017. On 7 July 2017 the Treaty on the Prohibition of Nuclear Weapons (TPNW) was passed with a vote of 122 nations in support, and it opened for signature on 20 September 2017. This "ban treaty" entered into force 90 d after 50 nations had ratified it, which was on 22 January 2021. As of this writing, 92 nations have signed it and 68 nations have ratified it.

The ban treaty states that,

> Each State Party undertakes never under any circumstances to: (a) Develop, test, produce, manufacture, otherwise acquire, possess or stockpile nuclear weapons or other nuclear explosive devices; (b) Transfer to any recipient whatsoever nuclear weapons or other nuclear explosive devices or con-

> trol over such weapons or explosive devices directly or indirectly; (c) Receive the transfer of or control over nuclear weapons or other nuclear explosive devices directly or indirectly; (d) Use or threaten to use nuclear weapons or other nuclear explosive devices; (e) Assist, encourage or induce, in any way, anyone to engage in any activity prohibited to a State Party under this Treaty; (f) Seek or receive any assistance, in any way, from anyone to engage in any activity prohibited to a State Party under this Treaty; (g) Allow any stationing, installation or deployment of any nuclear weapons or other nuclear explosive devices in its territory or at any place under its jurisdiction or control.

Unfortunately, the nine nuclear states have not yet ratified the treaty and have encouraged their allies to ignore it. But gradually, the will of the rest of the world demanding the abolition of nuclear weapons is being felt through pressure from increasing ratifications and signatories as well as the political pressure that comes from the TPNW's underlying arguments on the humanitarian consequences and risks of nuclear weapons.

6 ICAN Nobel Peace Prize

On 6 October 2017, it was announced that ICAN was awarded the 2017 Nobel Peace Prize "for its work to draw attention to the catastrophic humanitarian consequences of any use of nuclear weapons and for its ground-breaking efforts to achieve a treaty-based prohibition of such weapons." We were very happy that our work once again had such a positive influence.

When Beatrice Fihn, the director of ICAN, accepted the prize in her Nobel Peace Prize lecture on 10 December 2017 she said,

> If only a small fraction of today's nuclear weapons were used, soot and smoke from the firestorms would loft high into the atmosphere – cooling, darkening and drying the Earth's surface for more than a decade. It would obliterate food crops, putting billions at risk of starvation. Yet we continue to live in denial of this existential threat. The story of nuclear weapons will have an ending, and it is up to us what that ending will be. Will it be the end of nuclear weapons, or will it be the end of us? One of these things will happen. The only rational course of action is to cease living under the conditions where our mutual destruction is only one impulsive tantrum away.

7 Global famine, ultraviolet radiation, and extended oceanic response

While elated that our work helped lead to a treaty to ban nuclear weapons and to a Nobel Peace Prize, we still have many scientific questions to address, including several details of the amounts of fuel in target areas, the spread of urban fires, the altitudes of soot injection from mass fires, the impacts on the biota of ozone depletion and increased surface ultraviolet (UV) radiation, the spread of radioactive material in the atmosphere and oceans, and the impacts on agriculture and famine. So far, we have not been able to obtain funding for this work from the US Department of Energy, which makes our nuclear weapons, the US Department of Defense, which might actually use them, or the US Department of Homeland Security, whose job is to protect us from the indirect impacts of nuclear war. Our conventional funding agencies, the US National Science Foundation and NASA, also were not interested in considering proposals for a topic they found too radioactive.

We continued to do some research, using support for other questions, such as the impacts of volcanic eruptions on climate, but could not devote much time to it. Then one day in 2017, a program manager for the Open Philanthropy Project called Alan Robock to ask for feedback on a project they were considering related to climate intervention, a topic he was working on. After they talked, he asked her if they would consider funding our work on nuclear winter, which resulted in a very well funded 3-year project. He and Brian Toon put together a team to address many topics, including scenarios of future nuclear war, smoke emissions from cities and industrial areas that would be burned by nuclear war, impacts on ozone, and impacts on crops. In 2020 we were renewed for another 3 years.

This unexpected surge in our funding, from philanthropic sources, resulted in 18 journal articles and counting (http://climate.envsci.rutgers.edu/nuclear/#Publications, last access: 12 June 2023). Here we just describe a couple of them. Toon et al. (2019) realized that Pakistan and India may have 400 to 500 nuclear weapons by 2025 with yields from tested 12 to 45 kt values to a few hundred kilotonnes. They studied various scenarios of how India and Pakistan might fight a nuclear war with more and larger weapons than the Toon et al. (2007) case. See Fig. 2 for the global average surface air temperature changes and Table 1 for details on the scenarios. Lovenduski et al. (2020) used these simulations to study ocean acidification responses. They found that nuclear conflict has the potential to increase surface ocean pH and decrease aragonite saturation state, that the decrease in saturation state would exacerbate shell dissolution from anthropogenic ocean acidification, and that a regional nuclear conflict may have far-reaching effects on global ocean carbonate chemistry.

We conducted a study using multiple crop models for rice, wheat, maize, and soybeans, showing that the impacts

Table 1. Number of weapons on urban targets, yields, direct fatalities from the bomb blasts, and resulting number of people in danger of death due to famine for the different scenarios we studied. The 5 Tg case scenario is from Toon et al. (2007) for an India–Pakistan war taking place in 2008; the 16–47 Tg cases are from Toon et al. (2019) for an India–Pakistan war taking place in 2025; and the 150 Tg case is from Coupe et al. (2019), which assumes attacks on France, Germany, Japan, UK, USA, Russia, and China. The last column is the number of people who would starve by the end of year 2 when the rest of the population is provided with the minimum amount of food needed to survive, assumed to be a global average calorie intake of 1911 kcal per capita per day, and for no international trade, for a case in which 50 % of livestock crop feed was used for human consumption, and 50 % of livestock crop feed was used to raise livestock, using the latest complete data available, for the year 2010. For 2010, the total population of the nations used in the study was 6 700 000 000. There are many other scenarios in which these amounts of soot could be produced by a nuclear war, and the scenarios we use are only meant to be illustrative examples (Table 1 from Xia et al., 2022).

Soot	Number of weapons	Yield	Number of direct fatalities	Number of people without food at the end of year 2
5 Tg	100	15 kt	27 000 000	255 000 000
16 Tg	250	15 kt	52 000 000	926 000 000
27 Tg	250	50 kt	97 000 000	1 426 000 000
37 Tg	250	100 kt	127 000 000	2 081 000 000
47 Tg	500	100 kt	164 000 000	2 512 000 000
150 Tg	4400	100 kt	360 000 000	5 341 000 000
150 Tg	4400	100 kt	360 000 000	5 081 000 000*

* Assuming total household waste is added to food consumption.

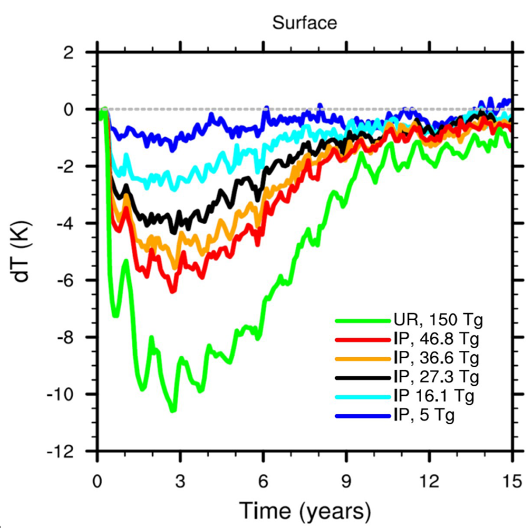

Figure 2. Global average surface air temperature changes for various scenarios of soot injection from fires, expressed in teragram (Tg). IP are various India–Pakistan nuclear war scenarios, and UR represents United States–Russia and allies. For details see Toon et al. (2019).

from 5 Tg of soot injected into the upper atmosphere would have global repercussions (Jägermeyr et al., 2020). Total single-year losses of 12 (±4) % quadruple the largest observed historical anomaly and exceed impacts caused by historic droughts and volcanic eruptions. Integrated food trade network analyses showed that domestic reserves and global trade could largely buffer the production anomaly in the first year. Persistent multiyear losses, however, would constrain domestic food availability and propagate to the Global South, especially to food-insecure countries. By year 5, maize and wheat availability would decrease by 13 % globally and by more than 20 % in 71 countries with a cumulative population of 1.3 billion people. In view of today's high level of nuclear risks, this study shows that a regional conflict using < 1 % of the worldwide nuclear arsenal could have adverse consequences for global food security unmatched in modern history.

Scherrer et al. (2020) used a fisheries model and showed that agricultural losses could not be offset by the world's fisheries, especially given widespread overfishing. Cold temperatures and reduced sunlight would decrease the growth of fish biomass, possibly as much as under unmitigated climate change. Although intensified postwar fishing could yield a small catch increase, dramatic declines would ensue due to overharvesting.

To examine the consequences for food production in each nation for various amounts of smoke, Xia et al. (2022) used crop and fishery models to estimate the impacts arising from six scenarios of stratospheric soot injection, predicting the total food calories available in each nation postwar after stored food is consumed. In quantifying impacts caused by climate change induced by the war, we showed that soot injections would lead to mass food shortages in almost all countries. Figures 3 and 4 show the number of people who would survive for two different scenarios, as described in Table 1. Consuming livestock and increased fishing would be unable to compensate for reduced crop output in most countries in the larger war scenarios. The sudden drop in light and ocean temperatures would severely limit the production of marine algae, the foundation of the marine food web, essentially cre-

Proportion of population that would starve to death
Partial Livestock Case, 37 Tg, 50% livestock feed to human consumption, no trade

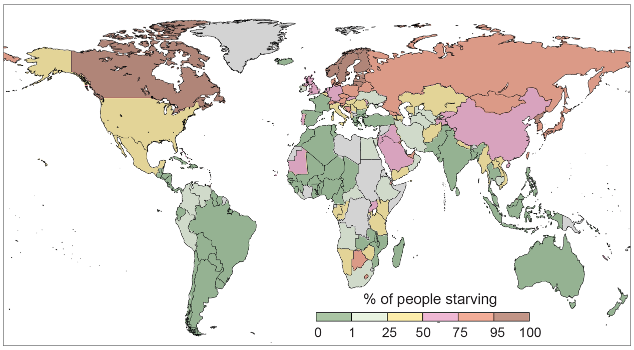

Figure 3. As described by Xia et al. (2022), we assumed that all stored food would be consumed within months after a nuclear war and calculated for the next year how many people would survive in each country if there was no international trade, if all people ate the minimum number of calories needed to support regular physical activity, and that once the available food ran out no food would be given to the fraction of the population that is predicted to die. That portion is plotted on this map for a 37 Tg soot injection, assuming that half the livestock was maintained, and the livestock crop feed that would have gone to the rest would go to humans. This would result in the death of 1–2 billion people. Of course, the fraction of the population given no food would likely attack those with food, leading to even more deaths.

Proportion of population that would starve to death
Partial Livestock Case, 150 Tg, 50% livestock feed to human consumption, no trade

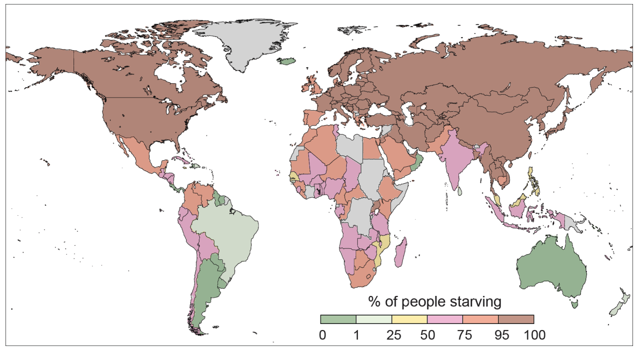

Figure 4. As Fig. 3 but for 150 Tg of smoke injected into the upper atmosphere. This would result in the death of most of humanity, more than 5 billion people out of an assumed population of 6.7 billion.

ating a famine in the ocean, with higher impacts to marine food sources in the Northern Hemisphere and coastal regions worldwide. In the larger war scenarios, this would pose intense limitations on fishing. Realistic adaptation measures we studied, such as reducing livestock production and using livestock food for humans or food waste reduction, would have limited impact on decreasingly available calories for the large smoke injection scenarios. Rapidly shifting agricultural production to new crops would be very difficult due to the period of only a few months before global food reserves are exhausted, as well as lack of seeds, fertilizer, labor, and agricultural knowledge.

The results in Figs. 3 and 4 depend on the assumptions made in our study. You might survive a nuclear war fought in the Northern Hemisphere by living in Argentina, Australia, or New Zealand. Indeed, because we assumed that international trade in food would collapse after a nuclear war, and these are all large food exporting nations, there would be enough locally produced food to feed their current populations. The climate changes induced by even the thickest smoke cloud from a US–Russian nuclear war would be lessened in these nations due to their Southern Hemisphere locations and their being surrounded by a large ocean. In contrast, the USA, Russia, and China would lose more than 90 % of their populations due to starvation. At higher latitudes in large continents, the impacts of climate change on agriculture and pasture would be exacerbated. In addition, the high populations in the USA, Russia, and China would require significant agricultural productivity that would be difficult with the persistent low temperatures in these countries even without a full nuclear winter. In a nuclear winter, several years with persistent sub-freezing temperature would halt agriculture.

However, there are factors that did not go into these maps that would have to be considered. Any comprehensive attempt to understand the full-scale consequences of such famine scenarios would have to include the impacts on social structures, likely societal collapse, infrastructure destruction, mass migratory movements, and psychological impacts, and those studies still need to be carried out. Also, we have not yet analyzed the impacts of radioactivity, but radioactivity impacts would largely be confined to regions near targets of nuclear weapons, and we here focus on the much greater impacts on food. The results shown in Figs. 3 and 4 are for the second year after the war, but the agricultural effects do not return to normal for several more years. Therefore, further loss of life would occur. There would be fewer remaining workers to do the farming but also fewer people to feed. We did not have the expertise to address issues such as a general societal collapse, infrastructure breakdown, psychological impacts, and probable halt to other supplies needed for farming, including fertilizer, seeds, fuel, and parts for machinery. All imported medical supplies and technology would also probably halt. We did not consider the impacts of additional ultraviolet radiation that would hit the surface due to ozone depletion in the stratosphere (Bardeen et al., 2021), and we did not consider direct radioactivity impacts on humans or radioactive contamination of food. Once the international banking system collapsed, would it even be possible to pay for imports if they were being traded? But one import would certainly increase. There would be flotillas of hungry people from the countries without food on their way south.

In addition to these catastrophic impacts, Harrison et al. (2022) found that the impacts of the surface cooling caused by the nuclear war would also include expansion of

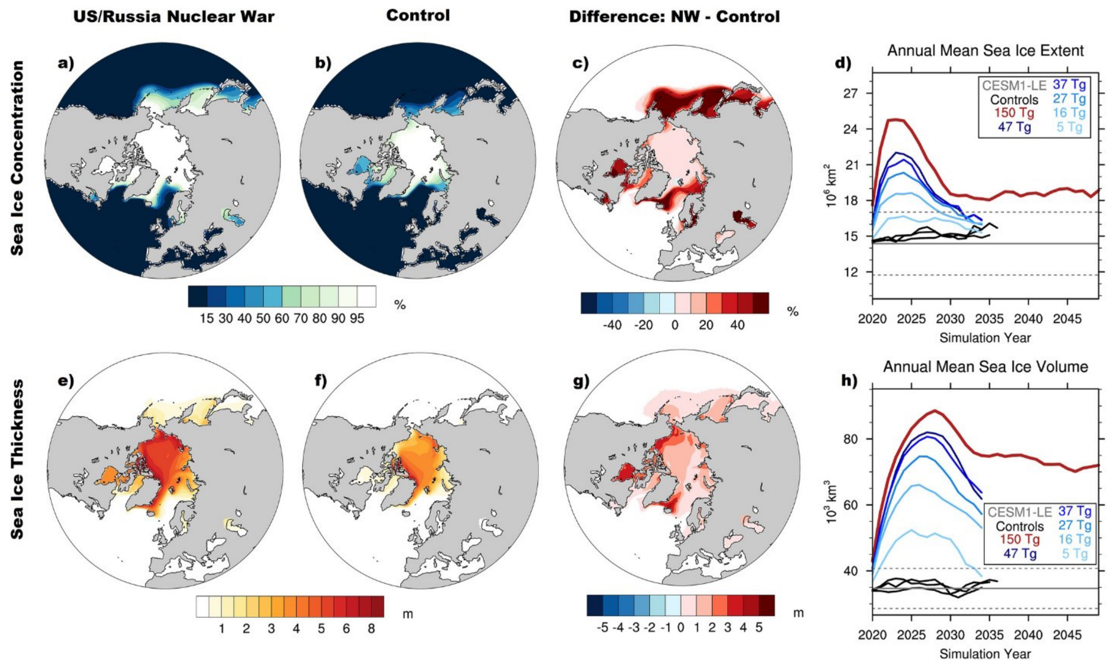

Figure 5. Postwar Arctic sea ice evolution. Arctic 2020–2025 mean sea ice concentration (%) for **(a)** the USA–Russia nuclear war (NW) scenario, **(b)** the control scenario, and **(c)** the difference in concentration between the two scenarios. Arctic mean sea ice thickness (m) for **(e)** the USA–Russia nuclear war scenario, **(f)** the control scenario, and **(g)** the difference in thickness between the two scenarios. The Northern Hemisphere annual mean time series of **(d)** sea ice extent and **(h)** sea ice volume is shown for all war scenarios (colors) and control scenarios (black), where the Community Earth System Model-Large Ensemble (CESM-LE) experiment mean (solid grey line) and standard deviation (dashed) over the preindustrial period are given to demonstrate the natural, internal variability within the model (Fig. 5 from Harrison et al., 2022).

sea ice in the first years after the war when food shortages would be highest, affecting shipping in regions into crucial ports where sea ice is not currently experienced, such as the Yellow Sea. This is illustrated in Fig. 5. In all scenarios, the ocean would cool rapidly but would not return to the prewar state when the smoke cleared. Instead, the ocean would take 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. Arctic sea ice would be left in a new state, a sort of "Nuclear Little Ice Age". Marine ecosystems would be highly disrupted by both the initial perturbation and the resulting new ocean state, resulting in impacts to ecosystem services worldwide, lasting for decades.

8 Recent impacts of our work

In 2022, after the stymied invasion of Ukraine by Russia, President Putin threatened that he might use nuclear weapons. We have tried to communicate our new results as widely as we can, making presentations at the 2022 Vienna Conference on the Humanitarian Impact of Nuclear Weapons, which was organized by Austria on the day before the First Meeting of States Parties of the TPNW, which took place in June 2022 in Vienna, and at the Tenth Review Conference of the Non-Proliferation Treaty at the United Nations in New York, in August 2022. We have noticed a strong uptick in the frequency of the use of the term "nuclear winter" on websites around the world. We think that our work, with this ubiquitous recognition of the possibility of nuclear winter following the use of any nuclear weapons, which could lead to escalation, is reducing the chance of that happening. But we do not know how to measure this impact.

However, there is evidence of awareness of our work in statements from nuclear powers. A 3 January 2022 Joint Statement of the Leaders of the Five Nuclear-Weapon States on Preventing Nuclear War and Avoiding Arms Races said,

> The People's Republic of China, the French Republic, the Russian Federation, the United Kingdom of Great Britain and Northern Ireland, and the United States of America consider the avoidance of war between Nuclear-Weapon States and the reduction of strategic risks as our foremost responsibilities. We affirm that a nuclear war cannot be won and must never be fought... We remain committed to our Nuclear Non-Proliferation Treaty (NPT) obligations, including our Article VI obligation "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and

> on a treaty on general and complete disarmament under strict and effective international control."

On 27 October 2022, Pakistan's ambassador to the United States, Masood Khan, warned of a nuclear winter that could result from escalation of conflicts in Kashmir between nuclear-armed Pakistan and India (O'Connor, 2022). The 16 November 2022 G20 Bali Leaders' Declaration indirectly refers to nuclear winter, and included the following:

> It is essential to uphold international law and the multilateral system that safeguards peace and stability. This includes defending all the Purposes and Principles enshrined in the Charter of the United Nations and adhering to international humanitarian law, including the protection of civilians and infrastructure in armed conflicts. The use or threat of use of nuclear weapons is inadmissible.

But if the nuclear weapons states claim that the only reason they keep their nuclear weapons is for deterrence, that involves the threat of their use of nuclear weapons. So there is more work to do.

Several of us, Alan Robock, Brian Toon, Rich Turco, and Gera Stenchikov, received the 2022 Future of Life Award on 6 August 2022 in Brooklyn, "for reducing the risk of nuclear war by developing and popularizing the science of nuclear winter," along with Carl Sagan, Paul Crutzen, John Birks, and Jeannie Peterson. Lili Xia, Alan Robock and Brian Toon received the Global Peace and Health Award from the International Physicians for Prevention of Nuclear War and the Boston Chapter of Physicians for Social Responsibility, 1 October 2022. And Lili Xia, Alan Robock, and our coauthors of the Xia et al. (2022) paper were nominated for the 2022 Arms Control Persons of the Year in December, 2022.

9 What now?

We plan to continue our work to publicize the threat of nuclear weapons. While the number of countries that have signed and ratified the TPNW is slowly increasing, the nine nuclear states continue to ignore it. The recent United States Nuclear Posture Review took no steps to lower its nuclear arsenal. China is building more missile silos. Iran continues to seem to want to build its own nuclear arsenal. To repeat, there is still a lot of work to do, and some of the readers of *ACP* could help to do this work.

Data availability. Data for Fig. 1 come from https://thebulletin.org/nuclear-notebook/ (Bulletin of the Atomic Scientists, 2023). The other figures are from published papers, which should be consulted for the data.

Author contributions. AR wrote the first version of this paper, with contributions from all the other authors. AR drew Fig. 1, OBT and CGB drew Fig. 2, Lili Xia drew Figs. 3 and 4, and CSH and JC drew Fig. 5.

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