Opinion: How Fear of Nuclear Winter has Helped Save the World, So Far

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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.

Abstract

The direct effects of nuclear war would be horrific, with blast, 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 (ICAN) 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 and broadly communicate their results and work for the elimination of nuclear weapons.

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 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 targets 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.

91   The early nuclear winter simulations were limited by the climate models and computing

92   power available for the calculations. But the basic science seemed settled, as summarized by

93   Pittock et al. (1986), Turco et al. (1990), and Sagan and Turco (1990). We know of no climate

94   modeling done on this topic until the past 20 years, since the *Atmospheric Chemistry and Physics*

95   journal was founded. Each of the previous simulations addressed certain aspects of the climate

96   model response with simple climate models or with short simulations of low-resolution

97   atmospheric GCMs.

98   Aleksandrov and Stenchikov (1983) used a very-low-resolution (12°x15° lat-lon)

99   atmospheric GCM with only 2 levels in the vertical coupled to a mixed-layer ocean and annual

100 average solar radiation, and conducted one 400-day simulation. They forced the model with 150

101 Tg of smoke, the amount that would have been generated by about 1/3 of the U.S. and Soviet

102 nuclear arsenal at the time. Their simulation produced surface temperature changes to values far

103 below freezing, and an overturning atmospheric circulation cell transporting the aerosols globally.

104 MacCracken (1983) used a similar model and produced similar results.

105   Turco et al. (1983) gave the name "nuclear winter" to this work, capturing the forcing and

106 response in a two-word phrase. Their single column model was intended to simulate mid-continent

107 conditions as it had no surface heat capacity. They used many different scenarios and simulated

108 the detailed vertical patterns of climate response, but were not able to look at dynamical responses

109 or the spatial distribution of climate change.

110   In the next couple of years, the primitive, by today's standards, National Center for

111 Atmospheric Research atmospheric GCM was used by Covey et al. (1984) and Thompson (1985)

112 for short runs at different times of the year, validating the earlier GCM results of Aleksandrov and

113 Stenchikov (1983) and MacCracken (1983). Robock (1984) was the first to study the entire

118 seasonal cycle and interannual responses, using an energy-balance model with a mixed-layer

119 ocean. He found that snow and sea ice albedo feedbacks prolonged the cooling even though he

120 used the short atmospheric smoke lifetime from Turco et al. (1983). This result was later validated

121 with GCM simulations using a mixed-layer ocean (Schneider and Thompson, 1988; Ghan, 1991).

122 Malone et al. (1985) showed that lofting of aerosols in the summer due to solar heating would

123 prolong their lifetime, because they would be in the stratosphere where they could not be removed

124 by precipitation, but they used a model with a low top of the atmosphere (32 km) and were only

125 able to run it for 40 days.

126 Ghan et al. (1988) and Pittock et al. (1989) investigated the impacts of different

127 assumptions about smoke optical properties. The decade ended with Turco et al. (1990)

128 summarizing the work since the original Turco et al. (1983) paper, and showed that the conclusion

129 that a nuclear winter could result from nuclear war was still robust. However, there were still

130 details to be studied and they outlined some important questions about the emissions of smoke,

131 smoke properties, and climate response.

132 Another decade and a half passed before nuclear winter research got going again. Progress

133 in computing and climate modeling allowed investigations that previously were impossible. In the

134 1980s the fastest "supercomputers" were orders of magnitude slower and had orders of magnitude

135 less storage than the smartphones most of us carry around in our pockets today. Thus, simulations

136 had to ignore much of the physics and chemistry of the atmosphere and they could not represent

137 the full depth of the atmosphere or be run long enough to study the interannual response to a smoke

138 injection. Robock et al. (2007a) conducted climate model simulations with a then state-of-the-art

139 GCM, ModelE from the National Aeronautics and Space Administration Goddard Institute for

140 Space Studies (Schmidt et al., 2006), which included a module to calculate the transport and

142   removal of aerosol particles (Koch et al., 2006). The atmospheric model was connected to a full

143   ocean general circulation model with calculated sea ice, thus allowing the ocean to respond quickly

144   at the surface and on yearly time scales in the deeper ocean. Robock et al. (2007a) ran the

145   atmospheric portion of the model at 4°x5° latitude-longitude resolution, with 23 vertical layers

146   extending to a model top of 80 km. The coupled oceanic general circulation model (Russell et al.,

147   1995) had 13 layers and also a 4°x5° latitude-longitude resolution. Simulations were run over a

148   decade, not just a few weeks. This work extended the time and sophistication of climate model

149   capabilities, and showed a long time scale of climate response not possible with previous models.

150   For the first time, we learned that smoke would stay in the stratosphere for multiple years because

151   we could simulate the heating and lofting of the smoke, preventing it from quickly falling out of

152   the air. The basic conclusion that a large-scale nuclear conflict would have devastating climatic

153   consequences was not only supported, but strengthened.

154   Using simple scenarios of 50 Tg and 150 Tg of soot injected into the upper troposphere,

155   Robock et al. (2007a) found that indeed the 150 Tg scenario, an injection of soot which is still

156   possible from the use of the current U.S. and Russian nuclear arsenals (Toon et al., 2008), would

157   produce a nuclear winter. And they found that the climate effects would last for more than a

158   decade, as for the first time they were able to realistically simulate the lifetime of the soot particles

159   in the upper atmosphere. Coupe et al. (2019) repeated these experiments using the Community

160   Earth System Model-Whole Atmosphere Community Climate Model version 4 (WACCM4;

161   (Marsh et al., 2013; Bardeen et al., 2017), run at 1.9°x2.5° horizontal resolution with 66 layers

162   from the surface to 140 km, with full stratospheric chemistry and with the Community Aerosol

163   and Radiation Model for Atmospheres in the stratosphere allowing particle growth (Toon et al.,

164   1988; Turco et al., 1979; Bardeen et al., 2008, 2017). Remarkably, the Robock et al. (2007a) and

166 Coupe et al. (2019) models produced similar results. Nuclear winter, with below freezing

167 temperatures over much of the Northern Hemisphere during summer, would occur due to a

168 significant reduction of surface solar radiation due to smoke lofted into the stratosphere. The more

169 sophisticated aerosol representation in WACCM4 removes this smoke more quickly, but the

170 magnitude of the climate response is not reduced. In fact, the higher resolution WACCM4

171 simulates larger temperature and precipitation reductions than ModelE in the first few years

172 following a 150 Tg soot injection. A strengthening of the northern polar vortex is modeled during

173 winter by both models in the first year, contributing to above normal, but still below freezing,

174 temperatures in the Arctic and northern Eurasia.

175   After the August 6, 1945 atomic bombing of Hiroshima and the April 18, 1906 San

176 Francisco earthquake large firestorms pumped smoke into the stratosphere, and current nuclear

177 arsenals with much larger weapons would do the same when targeted on cities. Large

178 pyrocumulonimbus following forest fires were observed recently to inject smoke into the

179 stratosphere (e.g., Yu et al. 2019) and high-resolution modeling of city fires (Redfern et al., 2021),

180 as part of our research, further support the theory that stratospheric smoke injections occur.

181 **2. Reagan and Gorbachev**

182   In 1986 President Ronald Reagan of the U.S. and General Secretary Mikhail Gorbachev of

183 the Soviet Union took the first steps in history to reduce the numbers of nuclear weapons. When

184 the first nuclear winter results were produced by American (Turco et al., 1983; MacCracken, 1983;

185 Covey et al., 1984; Robock, 1984) and Russian (Aleksandrov and Stenchikov, 1983) scientists,

186 they were accepted by President Reagan and General Secretary Gorbachev. When asked about the

187 effects of nuclear war in a February 12, 1985 interview in the *New York Times* Reagan said, "A

188 great many reputable scientists are telling us that such a war could just end up in no victory for

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197 anyone because we would wipe out the earth as we know it. And if you think back to ... natural

198 calamities - back in the last century, in the 1800's, ... volcanoes - we saw the weather so changed

199 that there was snow in July in many temperate countries. And they called it the year in which there

200 was no summer. Now if one volcano can do that, what are we talking about with the whole nuclear

201 exchange, the nuclear winter that scientists have been talking about? It's possible ...." Gorbachev

202 said, "Models made by Russian and American scientists showed that a nuclear war would result

203 in a nuclear winter that would be extremely destructive to all life on Earth; the knowledge of that

204 was a great stimulus to us, to people of honor and morality, to act in that situation." (Hertsgaard,

205 2000).

206   By 1990 the arms race and Cold War had ended. Since then, the global nuclear arsenal has

207 been reduced by a factor of more than six. We were proud to have had a role in this, and that

208 science speaking truth to power had actually worked. Figure 1 shows the number of deployed

209 nuclear weapons on Earth over time. The Soviet Union did not end until 1991, long after the arms

210 race was over, so that is not what ended the nuclear arms race. But the total is still more than

211 12,000 nuclear weapons, and 4000 deployed, and all much larger than those used in the first

212 nuclear war in 1945. They can still produce nuclear winter (Robock et al., 2007a; Coupe et al.,

213 2019), so the problem is not yet solved.

214 **3. India and Pakistan**

215   There are now nine nuclear states. In addition to the U.S. and Russia, they are the United

216 Kingdom, France, China, India, Pakistan, Israel, and North Korea. As the current century began,

217 we went on to work on other issues, but as a low-grade war continued between India and Pakistan

218 along the Line of Control in Kashmir, journalists still wondered about the consequences should

219 one of these skirmishes escalate into a nuclear war. Brian Toon and Rich Turco led an effort to
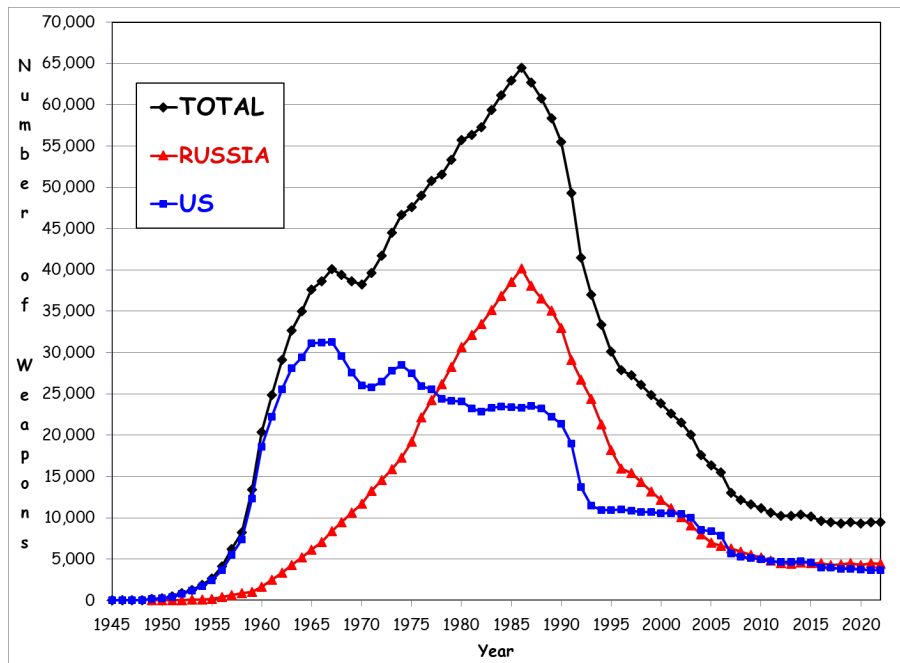
Figure 1. Time series of the total number of nuclear weapons on Earth, which after about 2005 excludes large numbers of tactical nuclear weapons as well as weapons in storage waiting to be dismantled. The total includes all nine nuclear-weapon states, but the other seven have at most a few hundred each. (Kristensen and Norris, 2015, updated.)

223 estimate how much smoke might be generated by such a war (Toon et al., 2007) and Robock et al.

224 (2007b) used a modern climate model to calculate the resulting climate change. With an estimated

225 5 Tg of soot from 100 city attacks using 15 kt atomic bombs, the same size that destroyed

226 Hiroshima on August 6, 1945, using the National Aeronautics and Space Administration/Goddard

227 Institute for Space Studies ModelE GCM they calculated global average cooling of more than 1

228 K, to a temperature colder than ever before experienced in recorded human history. This was the

229 first time an atmosphere ocean GCM had been used for this problem, and it was one that had a

230 complete stratosphere and mesosphere, allowing calculation of the lofting of the smoke by solar

231 heating and its global distribution. They calculated an e-folding lifetime for the smoke of 7 years,

232 with a climate response lasting more than a decade. Subsequent simulations with other GCMs

233 (Mills et al. 2014; Stenke et al., 2013; Pausata et al., 2016; Wagman et al, 2020) found very similar

234 results.

235 For the first time, the world came to the realization that not only would a nuclear war

236 between the two superpowers be a global catastrophe, but a war between any nuclear states using

237 less than 1% of the global arsenal would be similarly catastrophic. It would not be nuclear winter,

238 but could still serious consequences for agriculture and the world food supply unmatched in

239 modern history (Özdoğan et al., 2013; Xia et al., 2013, 2015).

240 **4. Humanitarian impacts conferences**

241 Alarmed by the continuing global threat of nuclear war, multiple activists from around the

242 world organized themselves into the International Campaign to Abolish Nuclear Weapons (ICAN).

243 ICAN (icanw.org), which now has 650 partner organizations from 110 nations worldwide. To

244 educate the world about the continuing threat of nuclear weapons, Norway, Mexico, and Austria

245 organized three international conferences on the humanitarian impacts of nuclear war, in Oslo,

246 Norway (March 2-3, 2013), Nayarit, Mexico (February 13-14, 2014), and Vienna, Austria

247 (December 8-9, 2014) as governmental expert conferences. ICAN and other non-governmental

248 organizations as well as academic experts were invited to participate. ICAN also organized

249 separate civil society events in the margins of the three governmental conferences, and campaigned

250 for states to attend. In addition to testimony from hibakusha survivors of the Hiroshima and

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253 Nagasaki bombings in 1945, our work on the agricultural impacts was presented in Norway by

254 Alan Robock and Ira Helfand, in Mexico by Alan Robock, and in Austria by Michael Mills.

255   Each of these conferences was attended by diplomatic representatives from over 100

256 nations. Many of them learned for the first time about the remote consequences for themselves of

257 a nuclear war fought on the other side of Earth, even if no bombs were dropped on them. They

258 were energized to do something about it.

259 **5. Treaty on the Prohibition of Nuclear Weapons**

260   In 2017, four countries, Austria, Ireland, Mexico, and South Africa, later expanded, to

261 include Brazil, Costa Rica, Indonesia, New Zealand, Nigeria, and Thailand, led a process to obtain

262 a mandate in the United Nations General Assembly to negotiate a treaty to ban nuclear weapons.

263 These states submitted resolutions in the General Assembly that garnered the necessary support to

264 conduct the negotiations. ICAN successfully campaigned all along for states to support this

265 activity, but it was a state-led process. At that time, nuclear weapons were the only weapons of

266 mass destruction that were not banned. Chemical and biological weapons had been banned, but

267 not the most destructive of all. Spurred by what they had learned at the humanitarian conferences

268 and activism by the ICAN partners in their nations and the International Committee of the Red

269 Cross, 135 nations, as well as members of civil society came to the UN General Assembly and

270 negotiated in March, June, and July 2017. Alan Robock made a presentation there on "Climate

271 effects of limited and large-scale nuclear war" on June 27, 2017. On July 7, 2017 the Treaty on

272 the Prohibition of Nuclear Weapons (TPNW) was passed with a vote of 122 nations in support,

273 and it opened for signature on September 20, 2017. The Ban Treaty entered into force 90 days

274 after 50 nations had ratified it, which was on January 22, 2021. As of this writing, 92 nations have

275 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 control 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 and 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 October 6, 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 December 10, 2017 she said, "If only a small fraction of today's nuclear weapons were

316 used, soot and smoke from the firestorms would loft high into the atmosphere - cooling, darkening

317 and drying the Earth's surface for more than a decade. It would obliterate food crops, putting

318 billions at risk of starvation. Yet we continue to live in denial of this existential threat. The story

319 of nuclear weapons will have an ending, and it is up to us what that ending will be. Will it be the

320 end of nuclear weapons, or will it be the end of us? One of these things will happen. The only

321 rational course of action is to cease living under the conditions where our mutual destruction is

322 only one impulsive tantrum away."

323 **7. Global Famine, Ultraviolet Radiation, and Extended Oceanic Response**

324   While elated that our work helped lead to a treaty to ban nuclear weapons and to a Nobel

325 Peace Prize, we still have many scientific questions to address, including several details of the

326 amounts of fuel in target areas, the spread of urban fires, the altitudes of soot injection from mass

327 fires, the impacts on the biota of ozone depletion and increased surface ultraviolet (UV) radiation,

328 the spread of radioactive material in the atmosphere and oceans, and the impacts on agriculture

329 and famine. So far, we have not been able to obtain funding for this work from the Department of

330 Energy, which makes our nuclear weapons, the Department of Defense, which might actually use

331 them, or the Department of Homeland Security, whose job is to protect us from the indirect impacts

332 of nuclear war. Our conventional funding agencies, the National Science Foundation and NASA

333 also were not interested in considering proposals for a topic they found too radioactive.

334   We continued to do some research, using support for other questions, such as the impacts

335 of volcanic eruptions on climate, but could not devote much time to it. Then one day in 2017, a

336 program manager for the Open Philanthropy Project, called Alan Robock to ask for feedback on a

337 project they were considering related to climate intervention, a topic he was working on. After

338 they talked, he asked her if they would consider funding our work on nuclear winter, which resulted

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341   in a very-well funded 3-year project. He and Brian Toon put together a team to address many

342   topics, including scenarios of future nuclear war, smoke emissions from cities and industrial areas

343   that would be burned by nuclear war, impacts on ozone, and impacts on crops. In 2020 we were

344   renewed for another 3 years.
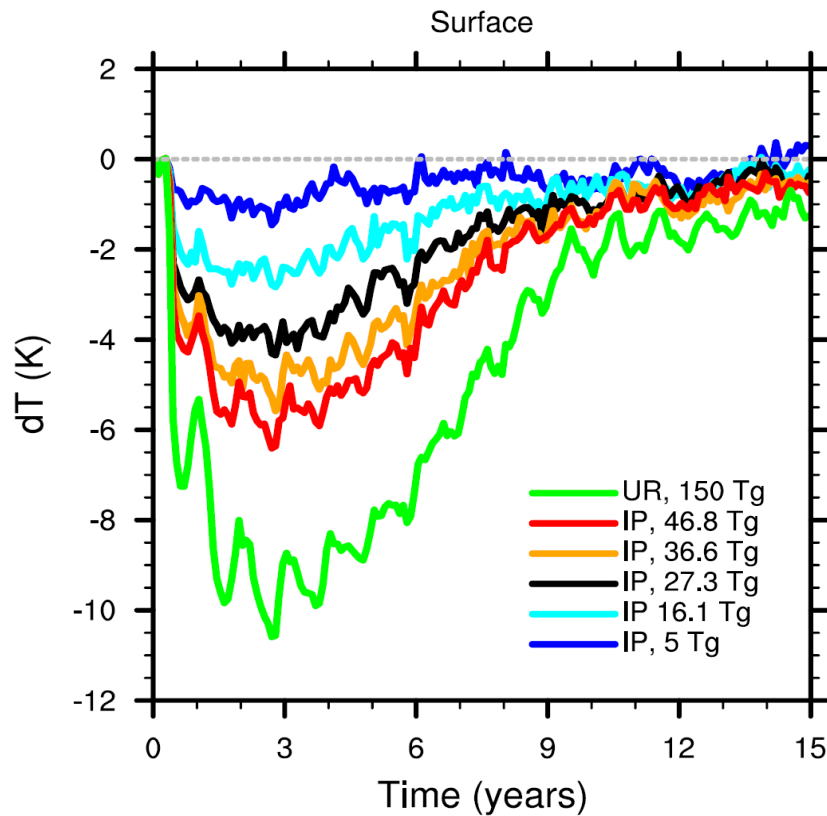
Figure 2. Global average surface air temperature changes for various scenarios of soot injection from fires, expressed in teragrams (Tg). IP are various India-Pakistan nuclear war scenarios and UR is United States-Russia and allies. For details see Toon et al. (2019).

345   This unexpected surge in our funding, from philanthropic sources, resulted in 17 journal

346   articles and counting (http://climate.envsci.rutgers.edu/nuclear/#Publications).   Here we just

347   describe a couple of them. Toon et al. (2019) realized that Pakistan and India may have 400 to

348   500 nuclear weapons by 2025 with yields from tested 12- to 45-kt values to a few hundred kilotons.

349   They studied various scenarios of how India and Pakistan might fight a nuclear war with more and

350   larger weapons than the Toon et al. (2007) case. See Figure 2 for the global average surface air

351   temperature changes and Table 1 for details on the scenarios. Lovenduski et al. (2020) used these

352   simulations to study ocean acidification responses. They found that nuclear conflict has the

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, U.K., U.S., 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/capita/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.

353 potential to increase surface ocean pH and decrease aragonite saturation state, that the decrease in

354 saturation state would exacerbate shell dissolution from anthropogenic ocean acidification, and

355 that a regional nuclear conflict may have far-reaching effects on global ocean carbonate chemistry.

356   We conducted a study using multiple crop models for rice, wheat, maize, and soybeans

357 showing that the impacts from 5 Tg of soot injected into the upper atmosphere would have global

358 repercussions (Jägermeyr et al., 2020). Total single-year losses of 12 (±4)% quadruple the largest

359 observed historical anomaly and exceed impacts caused by historic droughts and volcanic

360 eruptions. Integrated food trade network analyses showed that domestic reserves and global trade

361 could largely buffer the production anomaly in the first year. Persistent multiyear losses, however,

362 would constrain domestic food availability and propagate to the Global South, especially to food-

363 insecure countries. By year 5, maize and wheat availability would decrease by 13% globally and

364 by more than 20% in 71 countries with a cumulative population of 1.3 billion people. In view of

365 today's high level of nuclear risks, this study shows that a regional conflict using < 1% of the

366 worldwide nuclear arsenal could have adverse consequences for global food security unmatched

367 in modern history.

368   Scherrer et al. (2020) used a fisheries model and showed that agricultural losses could not

369 be offset by the world's fisheries, especially given widespread overfishing. Cold temperatures and

370 reduced sunlight would decrease the growth of fish biomass, possibly as much as under

371 unmitigated climate change. Although intensified postwar fishing could yield a small catch

372 increase, dramatic declines would ensue due to overharvesting.

373   To examine the consequences for food production in each nation for various amounts of

374 smoke, Xia et al. (2022) used crop and fishery models to estimate the impacts arising from six

375 scenarios of stratospheric soot injection, predicting the total food calories available in each nation

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

% of people starving

0   1   25   50   75   95   100
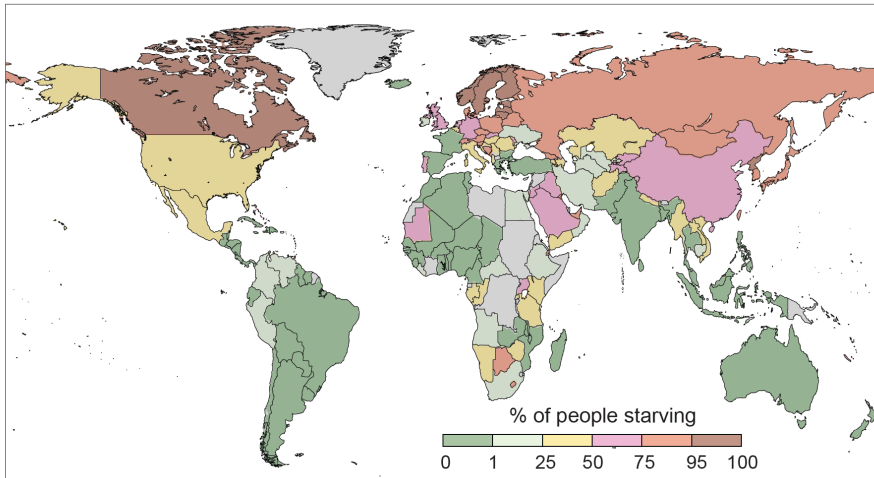
Figure 3. As described by Xia et al. (2022), we assumed that all stored food would be consumed within months after a nuclear war, and calculated for the next year how many people would survive in each country if there was no international trade, if all people ate the minimum number of calories needed 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, and 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.

382   post-war after stored food is consumed. In quantifying impacts caused by climate change induced

383   by the war, we showed that soot injections would lead to mass food shortages in almost all

384   countries. Figures 3 and 4 show the number of people who would survive for two different

385   scenarios, as described in Table 1. Consuming livestock and increased fishing would be unable to

386   compensate for reduced crop output in most countries in the larger war scenarios. The sudden

387   drop in light and ocean temperatures would severely limit the production of marine algae, the

388 foundation of the marine food web, essentially creating a famine in the ocean, with higher impacts

389 to marine food sources in the Northern Hemisphere and coastal regions world-wide. In the larger

390 war scenarios, this would pose intense limitations on fishing. Realistic adaptation measures we

391 studied, such as reducing livestock production and using livestock food for humans, or food waste

392 reduction, would have limited impact on decreasingly available calories for the large smoke

393 injection scenarios. Rapidly shifting agricultural production to new crops would be very difficult

394 due to the period of only a few months before global food reserves are exhausted, as well as lack

395 of seeds, fertilizer, labor, and agricultural knowledge.

396   The results in Figures 3 and 4 depend on the assumptions made in our study. You might

397 survive a nuclear war fought in the Northern Hemisphere by living in Argentina, Australia, or New

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

Figure 4. As Figure 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.

398 Zealand. Indeed, because we assumed that international trade in food would collapse after a

399 nuclear war, and these are all large food exporting nations, there would be enough locally-produced

400 food to feed their current populations. The climate changes induced by even the thickest smoke

401 cloud from a U.S.-Russia nuclear war would be lessened in these nations due to their Southern

402 Hemisphere locations and their being surrounded by a large ocean. In contrast, the U.S., Russia,

403 and China would lose more than 90% of their populations due to starvation. At higher latitudes in

404 large continents, the impacts of climate change on agriculture and pasture would be exacerbated.

405 In addition, the high populations in the U.S., Russia, and China would require significant

406 agricultural productivity that would be difficult with the persistent low temperatures in these

407 countries even without a full nuclear winter. In a nuclear winter, several years with persistent sub-

408 freezing temperature would halt agriculture.

409   However, there are factors that did not go into these maps that would have to be considered.

410 Any comprehensive attempt to understand the full-scale consequences of such famine scenarios

411 would have to include the impacts on social structures, likely societal collapse, infrastructure

412 destruction, mass migratory movements, and psychological impacts, and those studies still need to

413 be carried out. Also, we have not yet analyzed the impacts of radioactivity, but radioactivity

414 impacts would largely be confined to regions near targets of nuclear weapons, and we here focus

415 on the much greater impacts on food. The results shown in Figures 3 and 4 are for the second year

416 after the war, but the agricultural effects do not return to normal for several more years. Therefore,

417 further loss of life would occur. There would be fewer remaining workers to do the farming, but

418 also fewer people to feed. We did not have the expertise to address issues such as a general societal

419 collapse, infrastructure breakdown, psychological impacts, and probable halt to other supplies

420 needed for farming, including fertilizer, seeds, fuel and parts for machinery. All imported medical

424 supplies and technology would also probably halt. We did not consider the impacts of additional

425 ultraviolet radiation that would hit the surface due to ozone depletion in the stratosphere (Bardeen

426 et al., 2021), and did not consider direct radioactivity impacts on humans or radioactive

427 contamination of food. Once the international banking system collapsed, would it even be possible

428 to pay for imports, if they were being traded? But one import would certainly increase. There

429 would be flotillas of hungry people from the countries without food on their way south.
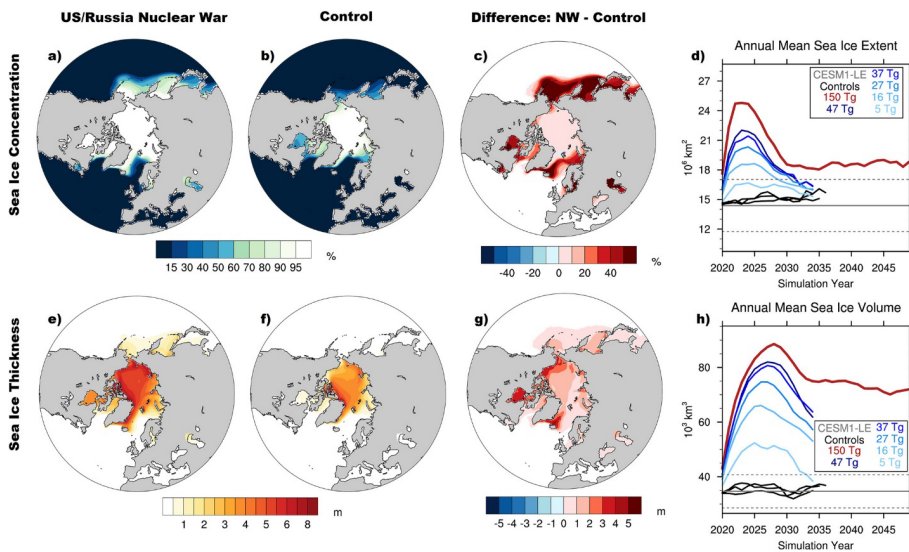
Figure 5. Post-war Arctic sea ice evolution. Arctic 2020-2025 mean sea ice concentration (%) for **(a)** the US-Russia Nuclear War (NW) scenario, **(b)** the control scenario, and **(c)** the difference in concentration between the two scenarios. Arctic mean sea ice thickness (m) for **(e)** the US/Russia 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 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. (Figure 5 from Harrison et al. (2022))

430   In addition to these catastrophic impacts, Harrison et al. (2022) found that the impacts of

431   the surface cooling caused by the nuclear war would also include expansion of sea ice in the first

432   years after the war when food shortages would be highest, affecting shipping in regions into crucial

433   ports where sea ice is not currently experienced, such as the Yellow Sea. This is illustrated in

434   Figure 5. In all scenarios, the ocean would cool rapidly but would not return to the pre-war state

435   when the smoke cleared. Instead, the ocean would take many decades to return to normal, and

436   some parts of the ocean would likely stay in the new state for hundreds of years or longer. Arctic

437   sea ice would be left in a new state, a sort of "Nuclear Little Ice Age." Marine ecosystems would

438   be highly disrupted by both the initial perturbation and the resulting new ocean state, resulting in

439   impacts to ecosystem services worldwide, lasting for decades.

440   **8. Recent impacts of our work**

441   In 2022, after the stymied invasion of Ukraine by Russia, President Putin threatened that

442   he might use nuclear weapons. We have tried to communicate our new results as widely as we

443   can, making presentations at the 2022 Vienna Conference on the Humanitarian Impact of Nuclear

444   Weapons, which was organized by Austria on the day before the First Meeting of States Parties of

445   the TPNW, which took place in June 2022 in Vienna, and at the Tenth Review Conference of the

446   Non-Proliferation Treaty at the United Nations in New York, in August, 2022. We have noticed

447   a strong uptick in the frequency of the use of the term "nuclear winter" on websites around the

448   world. We think that our work, with this ubiquitous recognition of the possibility of nuclear winter

449   following the use of any nuclear weapons, which could lead to escalation, is reducing the chance

450   of that happening. But we do not know how to measure this impact.

451   However, there is evidence of awareness of our work in statements from nuclear powers.

452   A January 3, 2022 Joint Statement of the Leaders of the Five Nuclear-Weapon States on Preventing

453   Nuclear War and Avoiding Arms Races said, "The People's Republic of China, the French

454   Republic, the Russian Federation, the United Kingdom of Great Britain and Northern Ireland, and

455   the United States of America consider the avoidance of war between Nuclear-Weapon States and

456   the reduction of strategic risks as our foremost responsibilities. We affirm that a nuclear war

457   cannot be won and must never be fought. ... We remain committed to our Nuclear Non-

458   Proliferation Treaty (NPT) obligations, including our Article VI obligation 'to pursue negotiations

459   in good faith on effective measures relating to cessation of the nuclear arms race at an early date

460   and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and

461   effective international control.'"

462   On October 27, 2022, Pakistan's Ambassador to the United States, Masood Khan, warned

463   of a nuclear winter that could result from escalation of conflicts in Kashmir between nuclear-armed

464   Pakistan and India (O'Connor, 2022). The November 16, 2022 G20 Bali Leaders' Declaration

465   indirectly refers to nuclear winter, and included, "It is essential to uphold international law and the

466   multilateral system that safeguards peace and stability. This includes defending all the Purposes

467   and Principles enshrined in the Charter of the United Nations and adhering to international

468   humanitarian law, including the protection of civilians and infrastructure in armed conflicts. The

469   use or threat of use of nuclear weapons is inadmissible." But if the nuclear weapons states claim

470   that the only reason they keep their nuclear weapons is for deterrence, that involves the threat of

471   their use of nuclear weapons. So there is more work to do.

472   Several of us, Alan Robock, Brian Toon, Rich Turco, and Gera Stenchikov, received the

473   2022 Future of Life Award on August 6, 2022 in Brooklyn, "for reducing the risk of nuclear war

474   by developing and popularizing the science of nuclear winter," along with Carl Sagan, Paul

475   Crutzen, John Birks, and Jeannie Peterson. Lili Xia, Alan Robock and Brian Toon received the

476 Global Peace and Health Award from the International Physicians for Prevention of Nuclear War

477 and the Boston Chapter of Physicians for Social Responsibility, October 1, 2022. And Lili Xia,

478 Alan Robock, and our coauthors of the Xia et al. (2022) paper were nominated for the 2022 Arms

479 Control Persons of the Year in December, 2022.

480 **9. What now?**

481 We plan to continue our work to publicize the threat of nuclear weapons. While the number

482 of countries that have signed and ratified the TPNW is slowly increasing, the nine nuclear states

483 continue to ignore it. The recent United States Nuclear Posture Review took no steps to lower its

484 nuclear arsenal. China is building more missile silos. Iran continues to seem to want to build its

485 own nuclear arsenal. To repeat, there is still a lot of work to do, and some of the readers of *ACP*

486 could help to do this work.

487

488 **Author contributions.** AR wrote the first version of this paper, with contributions from all the

489 other authors. AR drew Figure 1, OBT and CGB drew Figure 2, Lili Xia drew Figures 3 and 4,

490 and CSH and JC drew Figure 5.

491

492 **Competing interests.** The authors declare that they have no conflict of interest.

493

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497

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