1   **Opinion: How Nuclear Winter has Saved the World, So Far**
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32   *This article is dedicated to Paul Crutzen (1955-2021).*

33   *Along with John Birks, he pointed out that nuclear war would produce massive smoke clouds,*

34   *which led directly to nuclear winter theory.*

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36

37   **Abstract**

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39   The direct effects of nuclear war would be horrific, with blast, fires, and radiation killing

40 and injuring many people. But in 1983, United States and Soviet Union scientists showed that a

41 nuclear war could also produce a nuclear winter, with catastrophic consequences for global food

42 supplies for people far removed from the conflict. Smoke from fires ignited by nuclear weapons

43 exploded on cities and industrial targets would block out sunlight, causing dark, cold, and dry

44 surface conditions, producing a nuclear winter, with surface temperatures below freezing even in

45 summer for years. Nuclear winter theory helped to end the nuclear arms race in the 1980s and to

46 produce the Treaty on the Prohibition of Nuclear Weapons in 2017, which led to the 2017 Nobel

47 Peace Prize. Because awareness of nuclear winter is now widespread, nuclear nations have so

48 far not used nuclear weapons. But the mere existence of nuclear weapons means that they can be

49 used, by unstable leaders or because of an accident, computer malfunction, sensor malfunction,

50 human error, or terrorism. Because they cannot be used without the danger of escalation and a

51 global humanitarian catastrophe, and because of recent threats to use them by Russia, it is even

52 more urgent for scientists to broadly communicate their results and work for the elimination of

53 nuclear weapons.

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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 could 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.

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

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

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

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

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

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

84   atmospheric GCMs. Robock et al. (2007a) for the first time used a coupled atmosphere-ocean

85   GCM run continuously for multiple 10-yr simulations and with a model top at the mesopause.

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

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

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

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

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

91   below freezing, and an overturning atmospheric circulation cell transporting the aerosols

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

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

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

95   continent conditions as it had no surface heat capacity. They used many different scenarios and

96   simulated the detailed vertical patterns of climate response, but were not able to look at

97   dynamical responses or the spatial distribution of climate change.

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

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

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

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

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

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

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

105 validated with GCM simulations using a mixed-layer ocean (Schneider and Thompson, 1988;

106 Ghan, 1991). Malone et al. (1985) showed that lofting of aerosols in the summer due to solar

107 heating would prolong their lifetime, because they would be in the stratosphere where they could

108 not be removed by precipitation, but they used a model with a low top of the atmosphere (32 km)

109 and were only able to run it for 40 days.

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

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

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

113 conclusion that a nuclear winter could result from nuclear war was still robust. However there

114 were still details to be studied and the outlined some important questions about the emissions of

115 smoke, smoke properties, and climate response.

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

117 Progress in computing and climate modeling allowed investigations that previously were

118 impossible. Robock et al. (2007a) conducted climate model simulations with a then state-of-the-

119 art GCM, ModelE from the National Aeronautics and Space Administration Goddard Institute

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

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

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

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

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

125 layers extending to a model top of 80 km. The coupled oceanic general circulation model

126 (Russell et al., 1995) had 13 layers and also a 4°x5° latitude-longitude resolution. Simulations

127 were run over a decade, not just a few weeks. This work extended the time and sophistication of

128 climate model capabilities, and showed a long time scale of climate response not possible with

129 previous models. Yhe basic conclusion that a large-scale nuclear conflict would have

130 devastating climatic consequences was not only supported, but strengthened.

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

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

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

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

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

136 particles in the upper atmosphere. Coupe et al. (2019) repeated these experiments using the

137 Community Earth System Model-Whole Atmosphere Community Climate Model version 4

138 (WACCM4; (Marsh et al., 2013; Bardeen et al., 2017), run at 1.9°x2.5° horizontal resolution

139 with 66 layers from the surface to 140 km, with full stratospheric chemistry and with the

140 Community Aerosol and Radiation Model for Atmospheres in the stratosphere allowing particle

141 growth (Toon et al., 1988; Turco et al., 1979; Bardeen et al., 2008, 2017). Remarkably, the

142 Robock et al. (2007a) and Coupe et al. (2019) models produced similar results. Nuclear winter,

143 with below freezing temperatures over much of the Northern Hemisphere during summer, would

144 occur due to a significant reduction of surface solar radiation due to smoke lofted into the

145 stratosphere. The more sophisticated aerosol representation in WACCM4 removes this smoke

146 more quickly, but the magnitude of the climate response is not reduced. In fact, the higher

147 resolution WACCM4 simulates larger temperature and precipitation reductions than ModelE in

148 the first few years following a 150 Tg soot injection. A strengthening of the northern polar

149 vortex is modeled during winter by both models in the first year, contributing to above normal,

150 but still below freezing, temperatures in the Arctic and northern Eurasia.

151 Observations of firestorms after the August 6, 1945 atomic bombing of Hiroshima and

152 the April 18, 1906, San Francisco earthquake pumped smoke into the stratosphere, and are

153 evidence of how much larger fires started by nuclear bombing of cities would do the same.

154 Large pyrocumulonimbus stratospheric injection following forest fires (e.g., Yu et al. 2019) and

155 high-resolution modeling of city fires (Redfern et al., 2021), as part of our research, further

156 support the theory.

157 **2. Reagan and Gorbachev**

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

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

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

161 MacCracken (1983); Covey et al., 1984; Robock, 1984) and Russian (Aleksandrov and

162 Stenchikov, 1983) scientists, they were accepted by President Reagan and General Secretary

163 Gorbachev. When asked about the effects of nuclear war in a February 12, 1985 interview in the

164 *New York Times* Reagan said, "A great many reputable scientists are telling us that such a war

165 could just end up in no victory for anyone because we would wipe out the earth as we know it.

166 And if you think back to ... natural calamities - back in the last century, in the 1800's, ...

167 volcanoes - we saw the weather so changed that there was snow in July in many temperate

168 countries. And they called it the year in which there was no summer. Now if one volcano can

169 do that, what are we talking about with the whole nuclear exchange, the nuclear winter that

170   scientists have been talking about? It's possible ...." Gorbachev said, "Models made by Russian

171   and American scientists showed that a nuclear war would result in a nuclear winter that would be

172   extremely destructive to all life on Earth; the knowledge of that was a great stimulus to us, to

173   people of honor and morality, to act in that situation." (Hertsgaard, 2000).

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

175   has been reduced by a factor of four. We were proud to have had a role in this, and that science

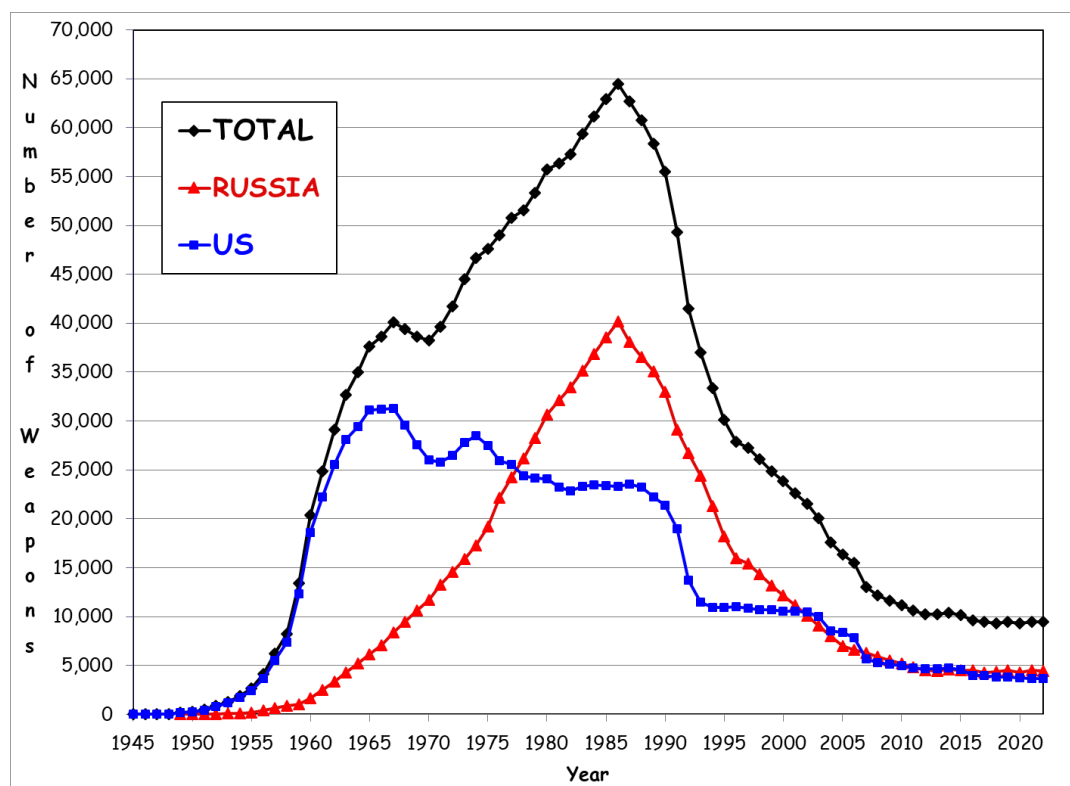176   speaking truth to power had actually worked. Figure 1 shows the number of deployed nuclear

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.)

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

178   was over, so that is not what ended the nuclear arms race. But the total is still around 10,000

179   nuclear weapons, deployed, and all much larger than those used in the first nuclear war in 1945.

180   They can still produce nuclear winter (Robock et al., 2007a; Coupe et al., 2019), so the problem

181   is not yet solved.

182   **3. India and Pakistan**

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

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

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

186   Pakistan along the Line of Control in Kashmir, journalists still wondered about the consequences

187   should one of these skirmishes escalate into a nuclear war. Brian Toon and Rich Turco led an

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

189   Robock et al. (2007b) used a modern climate model to calculate the resulting climate change.

190   With an estimated 5 Tg of soot from 100 city attacks using 15 kt atomic bombs, the same size

191   that destroyed Hiroshima on August 6, 1945, using the National Aeronautics and Space

192   Administration/Goddard Institute for Space Studies ModelE GCM they calculated global average

193   cooling of more than 1 K, to a temperature colder than ever before experienced in recorded

194   human history. This was the first time an atmosphere ocean GCM had been used for this

195   problem, and it was one that had a complete stratosphere and mesosphere, allowing calculation

196   of the lofting of the smoke by solar heating and its global distribution. They calculated an *e*-

197   folding lifetime for the smoke of 7 years, with a climate response lasting more than a decade.

198   Subsequent simulations with other GCMs (Mills et al. 2014; Stenke et al., 2013; Pausata et al.,

199   2016; Wagman et al, 2020) found very similar results.

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

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

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

203   winter, but could still serious consequences for agriculture and the world food supply unmatched

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

4. Humanitarian impacts conferences

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

207   the world organized themselves into the International Campaign to Abolish Nuclear Weapons

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

209   worldwide.   To educate the world about the continuing threat of nuclear weapons, ICAN

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

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

212   (December 8-9, 2014). In addition to testimony from hibakusha survivors of the Hiroshima and

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

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

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

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

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

218   They were energized to do something about it.

5. Treaty on the Prohibition of Nuclear Weapons

220   ICAN organized enough national delegations to the United Nations to negotiate a treaty

221   to ban nuclear weapons in 2017. At that time, nuclear weapons were the only weapons of mass

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

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223   the most destructive of all. Spurred by what they had learned at the humanitarian conferences

224   and activism by the ICAN partners in their nations, 135 nations, as well as members of civil

225   society came to the UN General Assembly and negotiated in March, June, and July 2017. Alan

226   Robock made a presentation there on "Climate effects of limited and large-scale nuclear war" on

227   June 27, 2017. On July 7, 2017 the Treaty on the Prohibition of Nuclear Weapons (TPNW) was

228   passed with a vote of 122 nations in support, and it opened for signature on September 20, 2017.

229   The Ban Treaty entered into force 90 days after 50 nations had ratified it, which was on January

230   22, 2021. As of this writing, 91 nations have signed it and 68 nations have ratified it.

231   The Ban Treaty states that "Each State Party undertakes never under any circumstances

232   to: (a) Develop, test, produce, manufacture, otherwise acquire, possess or stockpile nuclear

233   weapons or other nuclear explosive devices; (b) Transfer to any recipient whatsoever nuclear

234   weapons or other nuclear explosive devices or control over such weapons or explosive devices

235   directly or indirectly; (c) Receive the transfer of or control over nuclear weapons or other nuclear

236   explosive devices directly or indirectly; (d) Use or threaten to use nuclear weapons or other

237   nuclear explosive devices; (e) Assist, encourage or induce, in any way, anyone to engage in any

238   activity prohibited to a State Party under this Treaty; (f) Seek or receive any assistance, in any

239   way, from anyone to engage in any activity prohibited to a State Party under this Treaty; (g)

240   Allow any stationing, installation or deployment of any nuclear weapons or other nuclear

241   explosive devices in its territory or at any place under its jurisdiction or control."

242   Unfortunately, the nine nuclear states have not ratified the treaty, and have encouraged

243   their allies to ignore it. But at the first Meeting of States Parties of the TPNW, June 21-23, 2022,

244   in Vienna, and despite this public opposition, several key NATO states, Belgium, Germany, the

245   Netherlands, and Norway, as well as prospective members Finland and Sweden, attended as

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246 observers. So did U.S. ally Australia, which in October, 2022, at the UN for the first time did

247 not vote against a resolution urging states to sign the TPNW. Gradually, it seems, the TPNW is

248 getting more and more support.

249 **6. ICAN Nobel Peace Prize**

250 On October 6, 2017, it was announced that ICAN was awarded the 2017 Nobel Peace

251 Prize "for its work to draw attention to the catastrophic humanitarian consequences of any use of

252 nuclear weapons and for its ground-breaking efforts to achieve a treaty-based prohibition of such

253 weapons." We were very happy that our work once again had such a positive influence.

254 When Beatrice Fihn, the director of ICAN, accepted the prize in her Nobel Peace Prize

255 Lecture on December 10, 2017 she said, "If only a small fraction of today's nuclear weapons

256 were used, soot and smoke from the firestorms would loft high into the atmosphere - cooling,

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

258 putting billions at risk of starvation. Yet we continue to live in denial of this existential threat.

259 The story of nuclear weapons will have an ending, and it is up to us what that ending will be.

260 Will it be the end of nuclear weapons, or will it be the end of us? One of these things will

261 happen. The only rational course of action is to cease living under the conditions where our

262 mutual destruction is only one impulsive tantrum away."

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

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

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

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

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

268 radiation, and the impacts on agriculture and famine. So far, we had not been able to obtain
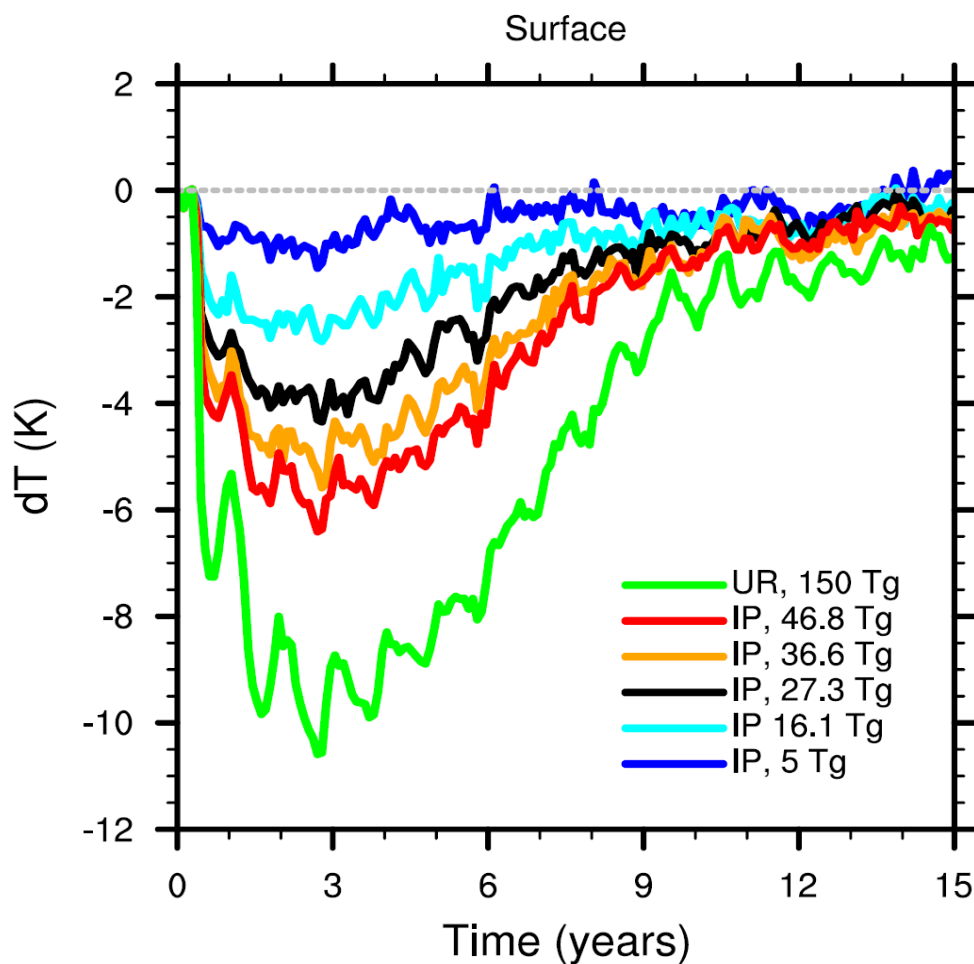
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Figure 2. Global average surface air temperature changes for various scenarios of soot injection from fires, expressed in teragrams (Tg). IP are various India-Pakistan nuclear war scenarios and UR is United States-Russia and allies. For details see Toon et al. (2019).

269   funding for this work from the Department of Energy, which makes our nuclear weapons, the

270   Department of Defense, which might actually use them, or the Department of Homeland

271   Security, whose job is to protect us from the indirect impacts of nuclear war. Our conventional

272   funding agencies, the National Science Foundation and NASA also were not interested in

273   considering proposals for a topic they found too radioactive.

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

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

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

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

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

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

280   many topics, including scenarios of future nuclear war, smoke emissions from cities and

281   industrial areas that would be burned by nuclear war, impacts on ozone, and impacts on crops.

282   In 2020 we were renewed for another 3 years.

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

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

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

286   500 nuclear weapons by 2025 with yields from tested 12- to 45-kt values to a few hundred

287   kilotons. They studied various scenarios of how India and Pakistan might fight a nuclear war

288   with more and larger weapons than the Toon et al. (2007) case. See Figure 2 for the global

289   average surface air temperature changes and Table 1 for details on the scenarios. Lovenduski et

290   al. (2020) used these simulations to study ocean acidification responses. They found that nuclear

291   conflict has the potential to increase surface ocean pH and decrease aragonite saturation state,

292   that the decrease in saturation state would exacerbate shell dissolution from anthropogenic ocean

293   acidification, and that a regional nuclear conflict may have far-reaching effects on global ocean

294   carbonate chemistry.

295   We conducted a study using multiple crop models showed that the impacts from 5 Tg of

296   soot injected into the upper atmosphere would have global repercussions (Jägermeyr et al.,

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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 world population was 6,703,000,000. 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.

2020), modeling the impacts on major crops, rice, wheat, maize, and soybeans. 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 increasing instability in South Asia, this

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305 study shows that a regional conflict using < 1% of the worldwide nuclear arsenal could have

306 adverse consequences for global food security unmatched in modern history.

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

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

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

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.

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

311 increase, dramatic declines would ensue due to overharvesting.

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

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

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

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

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

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

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

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

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

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

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

323 the larger war scenarios, this would pose intense limitations on fishing. Realistic adaptation

324 measures we studied, such as reducing livestock production and using livestock food for humans,

325 or food waste reduction, would have limited impact on decreasingly available calories for the

326 large smoke injection scenarios. Rapidly shifting agricultural production to new crops would be

327 very difficult due to the period of only a few months before global food reserves are exhausted,

328 as well as lack of seeds, fertilizer, labor, and agricultural knowledge.

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

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

331 New Zealand. Indeed, because we assumed that international trade in food would collapse after

332 a nuclear war, and these are all large food exporting nations, there would be enough locally-
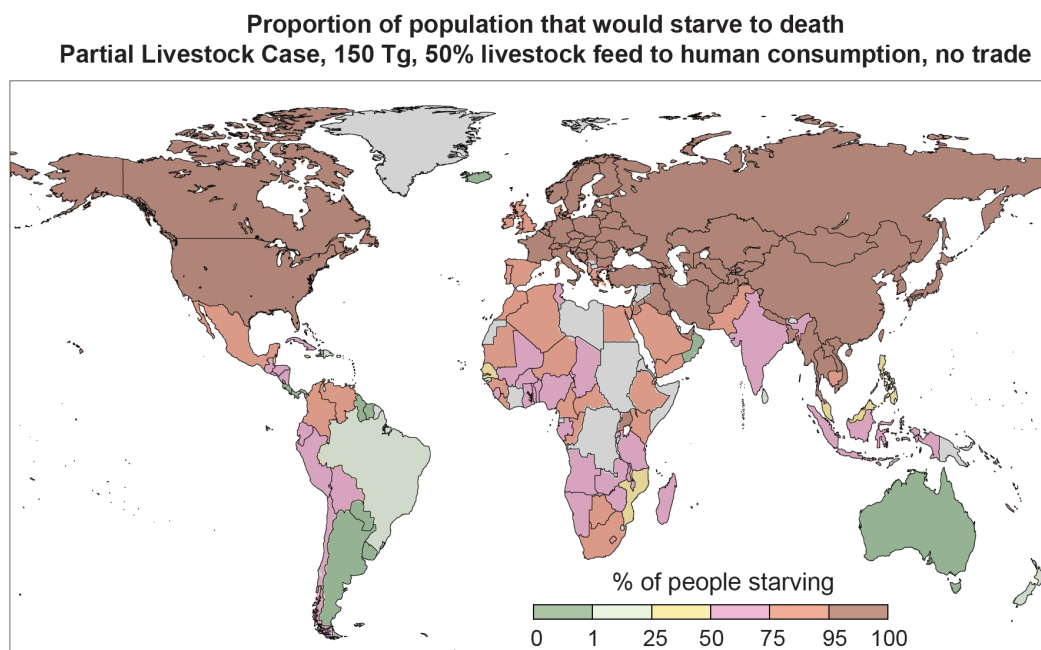
Proportion of population that would starve to death
Partial Livestock Case, 150 Tg, 50% livestock feed to human consumption, no trade

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.

333 produced food to feed their current populations. The climate changes induced by even the

334 thickest smoke cloud from a U.S.-Russia nuclear war would be lessened in these nations due to

335 their lower latitude and their being surrounded by a large ocean. In contrast, the U.S., Russia,

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

337 in large continents, the impacts of climate change on agriculture and pasture would be

338 exacerbated. In addition, the high populations in the U.S., Russia, and China would require

339 significant agricultural productivity that would be difficult with the persistent low temperatures

340 in these countries even without a full nuclear winter. In a nuclear winter, several years with

341 persistent sub-freezing temperature would halt agriculture.

19

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

343   considered. The results shown in Figures 3 and 4 are for the second year after the war, but the

344   agricultural effects do not return to normal for several more years. Therefore, further loss of life

345   would occur. There would be fewer remaining workers to do the farming, but also fewer people

346   to feed. We did not have the expertise to address issues such as a general societal collapse and

347   probable halt to other supplies needed for farming, including fertilizer, seeds, fuel and parts for
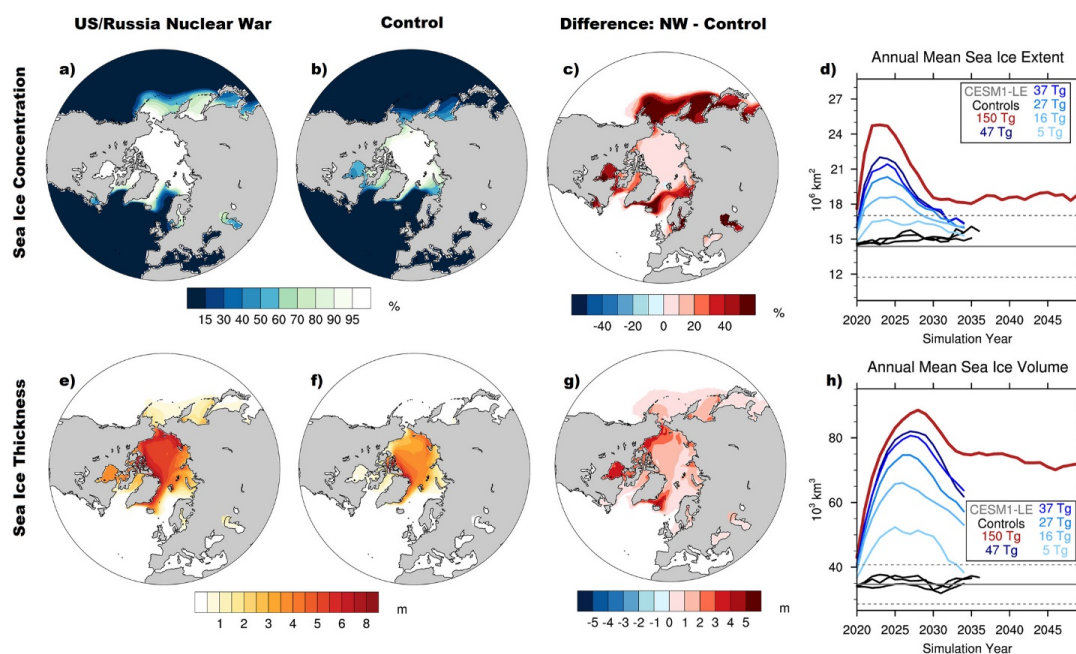

Figure 5. Post-war Arctic sea ice evolution. Arctic 2020-2025 mean sea ice concentration (%) for **(a)** the US-Russia Nuclear War (NW) scenario, **(b)** the control scenario, and **(c)** the difference in concentration between the two scenarios. Arctic mean sea ice thickness (m) for **(e)** the US/Russia 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))

348 machinery. All imported medical supplies and technology would also probably halt. We did not

349 consider the impacts of additional ultraviolet radiation that would hit the surface due to ozone

350 depletion in the stratosphere (Bardeen et al., 2021), and did not consider direct radioactivity

351 impacts on humans or radioactive contamination of food. Once the international banking system

352 collapsed, would it even be possible to pay for imports, if they were being traded? But one

353 import would certainly increase. There would be flotillas of hungry people from the countries

354 without food on their way south.

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

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

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

358 crucial ports where sea ice is not currently experienced, such as the Yellow Sea. This is

359 illustrated in Figure 5. In all scenarios, the ocean would cool rapidly but would not return to the

360 pre-war state when the smoke cleared. Instead, the ocean would take many decades to return to

361 normal, and some parts of the ocean would likely stay in the new state for hundreds of years or

362 longer. Arctic sea ice would be left in a new state, a sort of "Nuclear Little Ice Age." Marine

363 ecosystems would be highly disrupted by both the initial perturbation and the resulting new

364 ocean state, resulting in impacts to ecosystem services worldwide, lasting for decades.

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

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

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

368 can, making presentations at the First Meeting of States Parties of the TPNW, which took place

369 in June 2022 in Vienna, and at the Tenth Review Conference of the Non-Proliferation Treaty at

370 the United Nations in New York, in August, 2022. We have noticed a strong uptick in the

371 frequency of the use of the term "nuclear winter" on websites around the world. We think that

372 our work, with this ubiquitous recognition of the possibility of nuclear winter following the use

373 of any nuclear weapons, which could lead to escalation, is reducing the chance of that happening.

374 But we do not know how to measure this impact.

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

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

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

378 French Republic, the Russian Federation, the United Kingdom of Great Britain and Northern

379 Ireland, and the United States of America consider the avoidance of war between Nuclear-

380 Weapon States and the reduction of strategic risks as our foremost responsibilities. We affirm

381 that a nuclear war cannot be won and must never be fought. ... We remain committed to our

382 Nuclear Non-Proliferation Treaty (NPT) obligations, including our Article VI obligation 'to

383 pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms

384 race at an early date and to nuclear disarmament, and on a treaty on general and complete

385 disarmament under strict and effective international control.'"

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

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

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

389 Declaration indirectly refers to nuclear winter, and included, "It is essential to uphold

390 international law and the multilateral system that safeguards peace and stability. This includes

391 defending all the Purposes and Principles enshrined in the Charter of the United Nations and

392 adhering to international humanitarian law, including the protection of civilians and

393 infrastructure in armed conflicts. The use or threat of use of nuclear weapons is inadmissible."

22

394 But if the nuclear weapons states claim that the only reason they keep their nuclear weapons is

395 for deterrence, that involves the threat of their use of nuclear weapons. So there is more work to

396 do.

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

398 2022 Future of Life Award on August 6, 2022 in Brooklyn, "for reducing the risk of nuclear war

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

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

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

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

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

404 Arms Control Persons of the Year in December, 2022.

405 **9. What now?**

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

407 number of countries that have signed and ratified the TPNW is slowly increasing, the nine

408 nuclear states continue to ignore it. The recent United States Nuclear Posture Review took no

409 steps to lower its nuclear arsenal. China is building more missile silos. Iran continues to seem to

410 want to build its own nuclear arsenal. To repeat, there is still a lot of work to do, and some of the

411 readers of *ACP* could help to do this work.

412

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

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

415 and CSH and JC drew Figure 5.

416

23

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

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