Reassessing the "Nuclear Winter" Theory: Current Research on the Climate Effects of Nuclear War and Its Implications for Security and Nuclear Deterrence*

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Abstract

This paper attempts to re-evaluate scholarly research since the 1980s on the climate effects of nuclear war from a security perspective. The "nuclear winter" theory is epitomized by the work of the TTAPS team, comprised of Richard Turco, Carl Sagan, and others. It warned that the dust and smoke generated by a nuclear attack on an urban area could rise to and linger in the stratosphere, cause a significant drop in surface temperatures and block sunlight, leading to prolonged global cooling. While the study is credited with contributing to ending the nuclear arms race, it also became a target of widespread criticism due to its political impact. Following the end of the Cold War, attention to nuclear winter declined with reductions in nuclear arsenals. Since the second half of the 2000s, however, studies on the theory have evolved with advances in climate modeling, with many published papers showing that even a limited nuclear war would have severe climate and food production consequences. A subject of much academic debate, increasingly sophisticated research methods are being used to consider the nuclear winter theory, which still has important implications for international security and nuclear deterrence. At this juncture, it is incumbent on all nuclear weapon states to scientifically reassess the theory in light of their nuclear war plans and reconsider their approaches to nuclear risks.

Introduction

It is known that nuclear explosions produce physical phenomena, such as heat rays and blasts, shock waves, radioactivity, and electromagnetic pulses. However, a definitive opinion is still lacking regarding the medium- and long-term environmental and climatic consequences of nuclear war. While receiving minimal media attention,[1] analysis conducted in the 1970s of nuclear war's environmental impacts, particularly ozone depletion, initiated subsequent studies on the climate effects of nuclear war.[2] In the early 1980s, the "nuclear winter" hypothesis ("nuclear winter" theory) stimulated a prolific debate in academic journals. This theory posits that the dust and smoke generated by a nuclear attack on an urban area could rise to and linger in the stratosphere,

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1 Brian Martin, "Nuclear Winter: Science and Politics," *Science and Public Policy*, vol. 15, no. 5 (October 1988), pp. 321–334.
2 National Research Council, *Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonations* (Washington, DC: The National Academies Press, 1975).

causing a significant drop in surface temperatures.[3] In 1983, a conference on the climate effects of nuclear war was held, bringing together U.S. and Soviet scientists via satellite video, and attracted large media coverage.[4] This attention on the nuclear winter theory is credited with helping to end the nuclear arms race.[5] Authoritative academic organizations, such as the National Research Council (NRC), examined the climate effects of nuclear war and essentially acknowledged the nuclear winter theory, with a caveat that there remained areas where knowledge was insufficient.[6] Meanwhile, criticism arose that scientists should not exaggerate their hypotheses and use them to exercise political influence. Assessments of nuclear deterrence and varying views regarding strategic defense at the time may have contributed to the heated criticism. These debates came to a halt following the end of the Cold War, due in part to improved U.S.-Russia relations and progress in nuclear arms control and disarmament.[7] From the 2000s, advances in global warming research revived studies on the climate effects of nuclear war that used increasingly sophisticated climate models. For example, against the backdrop of the Kargil conflict, successive studies have been published showing that even a small-scale nuclear winter would lead to a food crisis ("nuclear famine").[8]

Nearly half a century has passed since the nuclear winter theory entered the academic debate, and a slew of new studies using climate models have been published in recent years. However, media and public attention on them has declined compared to the Cold War era, and sufficient academic debate has not been generated over the discussion and the validity of the research. How have the research methods used to study the nuclear winter theory evolved, and has it produced any findings? Does the nuclear winter theory have any implications for the current security environment and nuclear deterrence? These questions have yet to be adequately researched and clearly answered from a security perspective. I argue that a social scientific evaluation of the nuclear winter theory, one which pays attention to its linkage with nuclear proliferation and the relationship among nuclear weapon states, is essential for correctly understanding the significance of the theory.

Based on the above awareness of the issues, this paper focuses on the rise and development of the nuclear winter theory, the objections to the theory and their outcome, and the evolution of climate models. The paper considers how the theory developed in each decade from a security perspective and examines its implications for the present.

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3 Among the many scholarly papers published on this topic, this paper referred to the following, which was one of the first to cite the term "nuclear winter": Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack, and Carl Sagan, "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," *Science*, vol. 222, no. 4630 (December 23, 1983), pp. 1283–1292.

4 Paul R. Ehrlich et al., *The Cold and the Dark: The World after Nuclear War* (London: W. W. Norton & Company, 1984), p. xviii.

5 Alan Robock, "Nuclear Winter is a Real and Present Danger," *Nature*, vol. 473 (May 19, 2011), p. 275.

6 National Research Council, *The Effects on the Atmosphere of a Major Nuclear Exchange* (Washington, DC: The National Academies Press, 1985).

7 Paul N. Edwards, "Entangled Histories: Climate Science and Nuclear Weapons Research," *Bulletin of the Atomic Scientists*, vol. 68, no. 4 (July 1, 2012), p. 36.

8 Alexandra Witze, "How a Small Nuclear War Would Transform the Entire Planet," *Nature*, vol. 579 (March 16, 2020), pp. 485–487.

1. The Rise and Development of the Nuclear Winter Theory

(1) Environmental Impact Studies of Nuclear War in the 1970s

Research on the environmental effects of nuclear war was carried out in the 1970s, a time when both the United States and the Soviet Union had stockpiles of thermonuclear weapons that provided them with retaliatory second-strike capabilities, i.e., when the "balance of terror" was becoming normalized.[9] These studies focused solely on the environmental effects of ozone depletion that could result from nuclear explosions with massive yield.

An example is a 1975 NRC report on the long-term effects of nuclear explosions, which examined the post-nuclear war situation focusing on the effects of heat rays and radioactivity, including environmental effects. Specifically, the report assumed a nuclear war scenario in which nuclear weapons with a yield of 100,000 megatons would be assigned (hereafter yield refers to the total yield in hypothetical nuclear wars unless otherwise noted) and 100 million to 1 billion tons of dust would be injected into the stratosphere. These figures are comparable to the estimated amount of dust injected by the 1883 eruption of Mount Krakatoa in Indonesia, which may have lowered the Earth's average surface temperature by a few tenths of a degree centigrade, and forecast that terrestrial solar radiation would decrease by a few percent over a three-year period following nuclear war. Furthermore, simplified model calculations indicated that local disruption of ozone concentrations due to stratospheric heating after nuclear war, the propagation of stratospheric temperature changes to the troposphere, and a uniform 50% decrease in ozone concentrations could lower global average surface temperatures by several tenths of a degree centigrade. According to the report, even global average surface temperature changes by around 0.5°C could have serious impacts on regional climate, and the injection of dust and nitric oxides into the stratosphere by the outbreak of such a nuclear war could have severe climatological effects.[10]

In 1979, the Office of Technology Assessment (OTA) submitted a report on the effects of nuclear war to the U.S. Senate. This report likewise focused on analyzing the immediate effects of nuclear attack, and its environmental impact assessment referred to ozone depletion in the upper atmosphere over a few months to years following a nuclear attack. Specifically, based on multiple nuclear explosion scenarios with a yield of 1 megaton or more, the report suggested the possibility of ozone layer depletion and dilution due to injection of large amounts of nitrogen oxides into the stratosphere, and discussed concerns over serious climatic effects. At the same time, the report stated that the effects of ozone depletion cannot be measured and analyzed in detail, and that the possibility of ozone deficiency after nuclear war was becoming more doubtful year after year due to the development of multiple independently-targetable reentry vehicles (MIRVs) and the reduction in the number of warheads with ultra-high nuclear yield.[11]

The research reports above are both by an authoritative academic institution and government organization, respectively. Western academic journals continued to frequently cite the reports, especially the effects of nuclear war. At the same time, the views expressed in the reports prompted concerns, possibly because nuclear war posed a real threat in this era. For example, E. L. M. Burns,

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9 Albert Wohlstetter, "The Delicate Balance of Terror," *Foreign Affairs*, vol. 37, no. 2 (1959), pp. 213–214.

10 National Research Council, *Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonations*, pp. 6–7.

11 Michael Riordan, ed., *The Day after Midnight: The Effects of Nuclear War* (Palo Alto: Cheshire Books, 1982), pp. 124–125.

a retired lieutenant general of the Canadian Army and author of a book on national defense in the nuclear age, criticized that, while the NRC report gives the impression that the consequences of nuclear war do not concern the survival of the human race, a closer reading reveals that the report was forced to draw conclusions from few empirical data.[12] Lawrence Freedman, a distinguished British scholar of strategic studies, commended the OTA report for compiling known facts about the physical effects of nuclear war and examining its socioeconomic impact, yet noted that the effects were unrealistic and did not appeal to human emotions in any way.[13]

Notwithstanding the critiques, these are undoubtedly findings of first-rate research involving many scientists and experts about the effects of nuclear war at the time. The results of these studies, including those in support of and against nuclear war, played an important role in subsequent research.

(2) Nuclear Winter Theory in the 1980s

In the early 1980s, a series of studies focusing on the climate environmental impacts of nuclear war began to be published in academic journals, and the reactions to them gradually grew louder. The timing coincided with the new Cold War when the threat of nuclear war was acute. There was increasing concern over the United States and the Soviet Union seeking to win a nuclear war, which would fundamentally shake the conventional discourse on nuclear deterrence,[14] and such circumstances contributed to the rapid growth of this research.

One of the first studies conducted on the climate effects of nuclear war was the paper by Paul J. Crutzen and John W. Birks.[15] It was also at this time that Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack, and Carl Sagan published a paper that subsequently attracted media and political attention.[16] The lead author of the former paper was Crutzen, who later won the Nobel Prize in Chemistry for his work on the ozone hole. Alongside noting uncertainties, including perturbations in the heating rate associated with large-scale ozone depletion, the paper expressed concern that forest, urban, and oil field fires ignited by nuclear attacks and the shielding of sunlight by nitric oxide from the fires would cause extensive damage to agriculture in the Northern Hemisphere,[17] and offered a new perspective—the effects of fires—as an extension of the 1975 NRC report. The latter paper, on the other hand, began as a study of dust storms on the entire Mars planet observed by the Mariner 9 spacecraft.[18] In Martian dust storms, the temperature of the atmosphere increases as the sand rises to the upper layers of the atmosphere and absorbs solar radiation, while the temperature of the surface declines as the sunlight is prevented from reaching the surface due to the sand. When the storm subsides and the sand falls to the ground over several

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12 E. L. M. Burns, "Thinking about the Unthinkable," *Bulletin of the Atomic Scientist*s, vol. 32, no. 1 (January 1976), pp. 41–42.

13 Lawrence Freedman, "The Effects of Nuclear War: Office of Technology Assessment," *Futures*, vol. 12, no. 2 (April 1980), pp. 151–152.

14 Hugh Mehan, Charles E. Nathanson, and James M. Skelly, "Nuclear Discourse in the 1980s: the Unravelling Conventions of the Cold War," *Discourse & Society*, vol. 1, no. 2 (1990), p. 134.

15 Paul J. Crutzen and John W. Birks, "The Atmosphere after a Nuclear War: Twilight at Noon," *Ambio*, no. 11 (1982), pp. 114–125.

16 Turco et al., "Nuclear Winter," pp. 1283–1292.

17 Crutzen and Birks, "The Atmosphere after a Nuclear War," pp. 120–122.

18 Carl Sagan, "The Atmospheric and Climatic Consequences of Nuclear War," in Paul R. Ehrlich et al., *The Cold and the Dark*, pp. 3–4.

months, the atmosphere conversely cools and the ground surface warms from the sunlight. Based on the results of this research, Turco et al. next studied how the mixture of fine particles and ambient gases that rise into the stratosphere from volcanic eruptions on Earth affects the climate, taking into account the decrease in sunlight. They found that global surface temperatures dropped in many cases of volcanic eruptions, although modeling studies of interhemispheric transport of dust in the stratosphere are not without issues. Turco, Sagan, and others applied their findings to urban fires in the aftermath of nuclear war, and coined the term "nuclear winter" to describe the possible climate effects of nuclear war. The group of researchers became known as "TTAPS" derived from the initials of their surnames. One of them, Sagan, was a well-known astronomer and called attention to the threat of nuclear war and nuclear winter through various media.

TTAPS, believing that dust and smoke trigger nuclear winter, made the following assumptions based on knowledge accrued from atmospheric nuclear tests: a nuclear explosion with a yield of 1 megaton would generate 1 to 6 tons of dust with a size of about 0.1 micrometer in radius; and a large fire spanning more than 260 square kilometers caused by a 1-megaton attack on a city would produce 200 tons of smoke per 2.6 square kilometers. TTAPS estimated that 65 million tons of dust and 225 million tons of smoke would rise in the baseline scenario (nuclear weapons with a yield of 5,000 megatons are assigned to urban areas and major military targets). Incidentally, TTAPS gave several nuclear war scenarios that assign a yield of 100 megatons to 25,000 megatons but did not show the results of the respective calculations.[19]

In connection with volcanic eruptions and climate change, of note is the 1815 eruption of Mount Tambora in Indonesia, which is often cited in 1980s studies of the nuclear winter theory. In this eruption, plumes reached the stratosphere before spreading across the Earth and lingered for two years. In the following year (1816), crop failure in the West caused frequent food crises, and the year became known as the "year without a summer."[20] Michael Rowan-Robinson indicated that the dust and smoke generated in the TTAPS reference scenario is comparable to the amount of dust and smoke produced by the Mount Tambora eruption, and that the degree of dust uplift is proportional to the nuclear yield. He supported the preliminary findings presented by TTAPS, noting that a 1-megaton nuclear explosion would raise 10,000 to 30,000 tons of dust into the stratosphere, but that dust would not reach the stratosphere with a 100-kiloton nuclear explosion.[21] There is the famous question, why have the atmospheric nuclear tests since 1945 not resulted in a nuclear winter? Sagan explained that the tests have been conducted sporadically, and that the test sites were in shrub-covered deserts, coral atolls, tundra, and wastelands and thus did not ignite fires that produce vast amounts of dust and soot.[22]

Meanwhile, research on the nuclear winter theory widened in scope. In 1982, the journal *Ambio* published a special issue entitled, "Nuclear War: The Aftermath," compiled by the Royal Swedish Academy of Sciences. Articles on the nuclear winter theory were authored by experts in a range of fields from across the globe. With full-scale U.S.-Soviet nuclear war set as the reference scenario, the issue examines global environmental changes that survivors would face in the aftermath of a devastating nuclear war, beginning with the military implications of a nuclear attack

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19 Turco et al., "Nuclear Winter," p. 1284.

20 Michael Rowan-Robinson, *Fire and Ice: The Nuclear Winter* (London: Longman, 1985), p. 35.

21 Ibid.

22 Carl Sagan and Ricard Turco, *A Path Where No Man Thought* (London: Century, 1990), pp. 124–125.

on key worldwide military targets. It considers impacts from a variety of perspectives, such as the impact on the medical system, famine due to reduced food production capability, and catastrophic impact on the international economic system.[23] Additionally, the 1986 report on nuclear famine by the Scientific Committee on Problems of the Environment (SCOPE)-Environmental Effects of Nuclear War (ENUWAR) synthesizes the insights of global researchers, focusing on the effects of nuclear war on food production. Without using specific nuclear war scenarios, the report highlights the consequences of cooling by a few degrees centigrade as well as 5 to 20% reductions in sunlight during the vegetative growing season after nuclear war, and notes that disruption in food production may cause one to four billion people worldwide to suffer from famine.[24]

As such studies were published, authoritative academic organizations followed suit in studying the nuclear winter theory. In 1985, the National Academy of Sciences (NAS) compiled a report on the climatic effects of a major nuclear war at the request of the U.S. Department of Defense. The report adopted a scenario of using nuclear weapons with a yield of 6,500 megatons in a zone between 30° and 70° north latitude. It assumed that a nuclear attack with a yield of 1,500 megatons on military, economic, and political targets would cause surface nuclear explosions in a thousand urban areas, and that the remaining nuclear weapons with a yield of 5,000 megatons would be detonated at altitudes which maximize damage to the targets. This study, in which Toon, Turco, and others took part, indicated that the smoke, dust, and chemicals from the nuclear attack could stay in the atmosphere for several weeks, causing considerable temperature drops over a large segment of the northern temperate zone. Furthermore, the report mentioned that there are areas where scientific knowledge is inadequate, noting that accurate accounts cannot be provided on the response of the atmosphere, the redistribution and removal of depositions, the duration until the recovery of the environment, among other aspects. The report addressed the importance of better understanding smaller scale phenomena, as well as constructing atmospheric response models and increasing their credibility for the parameters of the phenomena.[25]

As described above, climate effects of nuclear war were studied in the 1980s, most famously the nuclear winter theory, and a series of research findings were published in academic journals. Many of these studies shared two commonalities: assuming a large-scale nuclear war; and discussing the implications of sunlight blocking and lower temperatures due to smoke and dust.

2. Objections to the Nuclear Winter Theory and Their Outcome

(1) Criticisms of the Nuclear Winter Theory in the 1980s

As mentioned, research on climate effects in the aftermath of nuclear war flourished in the 1980s. Due in part to its political impact, however, there was particularly strong resentment toward TTAPS which coined the term “nuclear winter.”[26] As the nuclear winter theory could impact the logic of nuclear deterrence and the foundations of the Strategic Defense Initiative

[23] Jeannie Peterson and Don Hinrichsen, eds., for the Royal Swedish Academy of Sciences, *Nuclear War: The Aftermath* (Oxford: Pergamon Press, 1983), pp.37–48, 59–71, 141–154.

[24] Mark A. Harwell and Christine C. Harwell, *Nuclear Famine: The Indirect Effects of Nuclear War* (Ithaca: Cornell University Press, 1986).

[25] National Research Council, *The Effects on the Atmosphere of a Major Nuclear Exchange*, pp. 1–7.

[26] Jill Lepore, “The Atomic Origins of Climate Science,” *New Yorker*, January 23, 2017, https://www.newyorker.com/magazine/2017/01/30/the-atomic-origins-of-climate-science.

(SDI),[27] the theory was sharply criticized by the military-industrial complex and some scientists.[28] Sagan, who had entered the media spotlight, became a target of some scientists for asserting that a nuclear winter would occur after a nuclear war, rather than promoting an academic debate regarding its probability.[29] That said, it could be argued that none of the criticisms led to the debunking or complete rejection of the nuclear winter theory. As is well known, a nuclear winter paper to be presented by TTAPS at an American Geophysical Union (AGU) meeting in 1982 was forced to be withdrawn by senior members and others of the National Aeronautics and Space Administration (NASA) Ames Research Center.[30] This is a case in point of political backlash by those who took a contrary position. Under pressure, TTAPS created its own forum for holding dialogues with global researchers from various fields and revealing the validity of the nuclear winter theory.[31]

Criticism of TTAPS by Edward Teller, who is considered one of the pioneers of U.S. nuclear weapons development, also garnered attention.[32] He wrote in his correspondence published in *Nature* in 1985 that the TTAPS study had not reached a firm scientific conclusion. Teller criticized Sagan and others for intentionally failing to mention a cited study's prediction that a nuclear winter would not occur in the Southern Hemisphere, and for over interpreting an earlier study's analysis regarding meteorite impacts and the mass extinction of dinosaurs 65 million years ago.[33] Sagan responded that Teller's criticism was emotionally charged by his unique belief that the existence of nuclear weapons contributes to all mankind.[34] Incidentally, Teller and Sagan gave testimonies on nuclear winter at a U.S. Senate hearing. Whereas Teller focused on attacking the hypothesis of TTAPS, Sagan explained throughout his testimony about the most extreme predictions for nuclear winter.[35] With regard to Teller's critique, Japanese meteorologist Masuda Yoshinobu, while acknowledging that meteorological phenomena have many unknowns, that the basis for assessing smoke has uncertainties, and that soot emissions from urban fires was a valid issue, noted that emphasizing uncertainties to criticize the limitations of assumptions-based theoretical research does nothing more than encourage agnosticism.[36]

Others besides Teller also critiqued TTAPS. John Maddox, for example, contends that the

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27 Matthew R. Francis, "When Carl Sagan Warned the World about Nuclear Winter," Smithsonianmag.com, January 26, 2021, https://www.smithsonianmag.com/science-nature/when-carl-sagan-warned-world-about-nuclear-winter-180967198/.

28 Carl Sagan and Richard P. Turco, "Nuclear Winter in the Post-Cold War Era," *Journal of Peace Research*, vol. 30, no. 4 (1993), p. 369.

29 Ingemar Ahlstrand, "Would Actions to Survive a Nuclear Winter Help Public Opinion See the Urgency of Preventive Measures?" in Håkan Wiberg, Ib Damgaard Petersen, and Paul Smoker, eds., *Inadvertent Nuclear War: The Implications of the Changing Global Order* (Oxford: Pergamon Press, 1993), p. 256.

30 Lawrence Badash, *A Nuclear Winter's Tale: Science and Politics in the 1980s* (Cambridge: MIT Press, 2009), p. 58.

31 Ibid., pp. 58–60.

32 "Civil Defense Can't Ward Off the Nuclear Winter," *New York Times*, January 12, 1984, https://www.nytimes.com/1984/01/12/opinion/l-civil-defense-can-t-ward-off-the-nuclear-winter-172023.html.

33 Edward Teller, "Correspondence: Climatic Change with Nuclear War," *Nature*, vol. 318 (November 14, 1985), p. 99.

34 Ashutosh Jogalekar, "The Curious Wavefunction: The Many Tragedies of Edward Teller," Scientific American Blog Network, January 15, 2014, https://blogs.scientificamerican.com/the-curious-wavefunction/the-many-tragedies-of-edward-teller/.

35 Francis, "When Carl Sagan Warned the World about Nuclear Winter."

36 Masuda Yoshinobu, *Kaku no Fuyu: Kakusenso to Kisho Ihen* [Nuclear Winter: Nuclear War and Meteorological Changes] (Tokyo: Soyu Shuppan, 1985), pp. 122–123.

TTAPS paper fails to discuss the assumptions in detail, oversimplifies the calculations of climate effects, and exaggerates the results. Rather than rigid approximations, Maddox suggested that a more sophisticated method be utilized to reanalyze how a complex atmospheric system would react in the aftermath of a nuclear war.[37] Maddox's point about the lack of details around the nuclear winter assumptions was itself criticized for neglecting the extensive footnotes in the 1983 TTAPS paper. On the other hand, the issue he raised about simplifying the calculations of the climate effects of nuclear war was regarded as valid, given the important role of oceans and winds in reducing temperature differences between land and ocean, or between the equator and polar regions.[38]

Thus, various views have been expressed to date on the TTAPS nuclear winter theory of the 1980s and on the structural critique of it. Some state that many of the researchers who opposed the nuclear winter theory were supporters of SDI, including Teller, and strongly criticized the nuclear winter hypothesis because, if correct, it could lead to the collapse of SDI as a defense policy, as well as other theories of nuclear strategy.[39] Conversely, some believe that scientists who were averse to SDI propaganda opposed the political aspects of Sagan's argument, fearing that it would give traction to the argument that strategic defense measures would prevent the onset of nuclear winter.[40] Some scholars expressed the view that the series of nuclear winter studies which appeared in peer-reviewed journals, unlike the reports of authoritative academic groups and government agencies, heightened concerns over the erosion of conventional positions of power in science and politics in Western countries.[41] Other scholars noted that Sagan did not limit his nuclear winter theory to scientific findings, even contributing an article advocating nuclear arsenal reductions to a foreign policy journal outside his field,[42] and for this reason, credited him for using nuclear winter as a political metaphor in order to link the nuclear winter theory to the global movement for nuclear disarmament.[43]

Considering the fluctuating discourse on nuclear deterrence, which was a concern in the early 1980s, it is not difficult to imagine that the media's attention to TTAPS intensified the academic debate on nuclear winter. Under these circumstances, the political nature of the nuclear winter theory during this period became even more pronounced when Sagan, who had been bearing the brunt of the criticism, entered the nuclear disarmament discussion.

(2) Oil Field Fires and the Nuclear Winter Theory in the 1990s

The nuclear winter theory stirred great controversy in the 1980s. Subsequent developments in the 1990s cannot be discussed without mentioning the debate on the climate effects of oil field

37 John Maddox, "Nuclear Winter and Carbon Dioxide," *Nature*, vol. 312 (December 13, 1984), p. 593.

38 Rowan-Robinson, *Fire and Ice*, pp. 61–63.

39 Francis, "When Carl Sagan Warned the World about Nuclear Winter."

40 Ahlstrand, "Would Actions to Survive a Nuclear Winter Help Public Opinion See the Urgency of Preventive Measures?" p. 257.

41 Matthias Dorries, "The Politics of Atmospheric Sciences: 'Nuclear Winter' and Global Climate Change," *OSIRIS*, vol. 26, no. 1 (2011), p. 219.

42 Carl Sagan, "Nuclear War and Climatic Catastrophe: Some Policy Implications," *Foreign Affairs*, vol. 62, no. 2 (Winter 1983), pp. 257–292.

43 William A. Ausmus, "Pragmatic Uses of Metaphor: Models and Metaphor in the Nuclear Winter Scenario," *Communication Monographs*, vol.65 (March 1998), p. 68.

fires. In the wake of Iraq's invasion of Kuwait, coalition forces began an air bombing campaign on Iraqi and Kuwaiti territories in January 1991, known as Operation Desert Storm, which led to the outbreak of the Gulf War. Iraqi forces then set fire to approximately 732 Kuwaiti oil fields. Turco, and Sagan and others were reported as saying that black soot from oil field fires could reach the stratosphere and circulate globally for long periods, triggering a small-scale nuclear winter. They reportedly estimated that summer temperatures in the Middle East and the Indian subcontinent would drop to around -7.8°C to 2.2°C (18˚F to 36˚F), that the monsoon's momentum would wane, and that soot would block sunlight, inflicting severe damage to agriculture and other industries. The study received media coverage and attracted attention.[44] At this time, Crutzen et al. also expressed similar concerns to those of TTAPS that were reported in the press.[45] However, contrary to reported predictions, the environmental impact of the oil field fires was only very minor. One of the underlying causes may be that the smoke from the oil field fires did not reach the stratosphere. Therefore, the total volume of smoke was much lower than that from fires caused by nuclear attacks on urban areas and oil refineries.[46] Regional characteristics were also thought to have been a factor. It has come to light that, in some oil fields with a high brine content, calcium chloride and sodium chloride crystals gave the smoke a white or gray color (25% of the oil field fires produced white smoke). Additionally, the inversion layer characteristic to the Gulf region kept soot in the lower atmosphere. The soot particles were mixed in with a large amount of water-absorbing sulfates, and it is believed that many smoke plumes disappeared in rain clouds.[47]

It turned out the concerns over the climate effects of oil field fires were unfounded. In this regard, it should be noted that there were some experts who immediately refuted the initially reported predictions of Turco, Sagan et al. In January 1991, Michael MacCracken et al. from the Lawrence Livermore National Laboratory in the United States used a computer model from the 1980s to calculate the rise of smoke plumes from burning around 3 million barrels at an oil field for 30 days, at 2 kilometers aloft and 5 kilometers aloft. MacCracken et al. found that the smoke would stay in the atmosphere for only five days in the former assumption and nine days in the latter assumption, and criticized that oil field fires would only have impacts similar to air pollution on a busy day at Los Angeles airport.[48] In addition, the British Meteorological Office issued a statement on January 17, 1991, stating that, according to its study, the global meteorological impact of oil field fires was likely to be small. At the same time, the Office noted that the obscuration of sunlight could significantly reduce local surface temperatures in Kuwait's downwind areas, resulting in the ripple effect of reduced precipitation in Southeast Asia during the summer monsoon season.[49]

To end the debate on the climate effects of oil field fires, Sagan wrote a letter to *Science* in 1991. According to the letter, assumptions of oil field fires suggest temperatures in South Asia could drop by 1 to 2°C if a significant amount of smoke rose to a high altitude. However, Sagan and Turco had added a caveat that they could not predict with certainty the actual extent of

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44 Sharon Begley, "Burning Oil Wells May Prove Less Damaging Than Thought," *Wall Street Journal*, March 21, 2003, p. B1; David Evans, "The Environmental Powder Keg in the Persian Gulf War," *Chicago Tribune*, January 18, 1991, p. D23.

45 Eliot Marshall, "'Nuclear Winter' from Gulf War Discounted," *Science*, vol. 251 (January 25, 1991), p. 372.

46 Alan Robock, "Nuclear Winter," *WIREs Climate Change*, vol. 1 (May/June 2010), p. 423.

47 Begley, "Burning Oil Wells May Prove Less Damaging Than Thought."

48 Marshall, "'Nuclear Winter' from Gulf War Discounted."

49 Ibid.

temperature decrease or the effect of soot on sunlight. He further noted that, although most of the smoke from the oil field fires did not reach the high altitude they had feared partly due to weather conditions, the validity of the nuclear winter theory is still supported by the fact that the climate effects of the smoke were observed in some parts of the war zone, and that the temperatures in the region dropped by an average of 4°C, i.e., even small amounts of soot can cause a drop in regional temperatures. He concluded that massive reductions in world nuclear arsenals would be the most reliable way to prevent a nuclear winter.[50] Sagan and Turco's 1993 paper further elaborated on this analysis, arguing that the amount of soot emitted from the oil field fires was only about one-ten thousandth of that expected in a nuclear war, that the size of the fires was small, and the distance between the oil fields was large, which prevented smoke plumes from rising due to the initial buoyant and kept the climate effects local. They reiterated that the decrease in sunshine and surface temperatures that occurred in Kuwait at around the time of the oil field fires supported the nuclear winter theory regarding the injection of soot into the stratosphere.[51]

Some have noted that the nuclear winter theory is not denied simply because smoke from the oil field fires had a minor climatic response,[52] while others have suggested that neither the nuclear winter theorists nor their critics have changed their perceptions or preconceptions at all throughout the debate over the Kuwait oil field fires.[53] Based on the turn of events, it is reasonable to conceive that the oil field fires do not conclusively disprove the study of the climate effects of nuclear war.

3. The Evolution of Climate Models and New Developments in the Theory of Nuclear Winter

(1) Post-Cold War Nuclear Disarmament Proposals and the Nuclear Winter Theory

The nuclear winter theory is credited with fueling a discussion and debate on deadly climate effects after nuclear war, spurring negotiations on nuclear arms control and disarmament between the United States and the Soviet Union.[54] This debate rapidly died down from the mid-1990s following the end of the Cold War. Against this backdrop, a look at the major nuclear disarmament proposals from 1990 to the 2000s reveals another interesting fact.

One of the leading nuclear disarmament proposals from the 1990s through the 2000s was the report of the Canberra Commission on the Elimination of Nuclear Weapons (1996).[55] Although the report discusses the physical damage from the use of nuclear weapons, it mentions nothing about the climate effects in the aftermath of nuclear war. The same is true of the Tokyo Forum for Nuclear Non-Proliferation and Disarmament's "Facing Nuclear Dangers: An Action Plan for the 21st Century" report (1999)[56] and the Weapons of Mass Destruction Commission's "Weapons

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50 Carl Sagan, "Letters: Kuwaiti Fires and Nuclear Winter," *Science*, vol. 254 (1991), p. 1434.

51 Sagan and Turco, "Nuclear Winter in the Post-Cold War Era," pp. 369–370.

52 Robock, "Nuclear Winter."

53 Badash, *A Nuclear Winter's Tale*, pp. 299–300.

54 Robock, "Nuclear Winter is a Real and Present Danger," p. 275.

55 Canberra Commission on the Elimination of Nuclear Weapons, *Report of the Canberra Commission on the Elimination of Nuclear Weapons* (Canberra: National Capital Printers, 1996).

56 "Facing Nuclear Dangers: An Action Plan for the 21st Century," The Report of the Tokyo Forum for Nuclear Non-Proliferation and Disarmament, Ministry of Foreign Affairs of Japan, July 25, 1999, https://www.mofa.go.jp/policy/un/disarmament/forum/tokyo9907/index.html.

of Terror: Freeing the World of Nuclear, Biological and Chemical Arms" report (2006).[57] On the other hand, the International Commission on Nuclear Non-proliferation and Disarmament (ICNND) refers to the nuclear winter effect in its report, "Eliminating Nuclear Threats: A Practical Agenda for Global Policymakers" (2009). The report notes that the 1980s nuclear winter theory contained ambiguities and received criticism, explaining that the research at the time relied on the first generation of climate models, and that more sophisticated climate models from the 2000s have revived the debate on the validity of the nuclear winter theory.[58] Furthermore, there is a report by Steven Starr, considered ICNND's internal research project, regarding the climate effects of nuclear attack. The report indicates that a localized nuclear war between India and Pakistan involving the exchange of around 100 weapons with a yield similar to that of the nuclear bomb dropped on Hiroshima and Nagasaki would produce as many fatalities as World War II and cause global climate impacts for a decade after the nuclear war.[59]

As shown above, references to nuclear winter vary considerably between the post-Cold War nuclear disarmament proposals depending on their year of publication. This may be because the existence of nuclear arms control agreements from the late 1980s to the early 1990s, such as the Intermediate-Range Nuclear Forces (INF) Treaty, the Strategic Arms Reduction Treaty I (START I), and the Presidential Nuclear Initiatives (PNIs), brought to the table challenges and issues more pressing than the climate effects of nuclear war when formulating those proposals. Conversely, from the late 1990s to the 2000s, the nuclear discussion shifted from nuclear arms reduction to counter-proliferation, with a series of events unfolding including the opening of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) signature and the rejection of its ratification by the U.S. Congress, as well as nuclear proliferation by India, Pakistan, and North Korea. It is therefore not hard to imagine that the nuclear disarmament proposals of the same period included the nuclear winter theory out of concern for the local use of nuclear weapons.

In any case, with the changing tide of nuclear weapon issues in the post-Cold War era, there were gradually fewer opportunities for media coverage of the nuclear winter theory, which once had rendered impacts not only on academic discussion but also on the shaping of public opinion on "nuclear war without winners." Not unrelated to this trend was the death in 1996 of famed astronomer Sagan, whose words and deeds captured the media's attention.

(2) Research on the Climate Effects of Limited Nuclear War and the Nuclear Famine Theory from the 2000s

Notwithstanding the foregoing, research on global environment and atmospheric science linked to the nuclear winter theory continued to evolve. Backed in part by improvements in computer calculation capabilities, climate models were developed for making predictions about the atmosphere, sunlight, and dust migration. This enabled the use of global environmental simulation technology to study the medium- and long-term effects of dust on sunlight, which was considered

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57 Weapons of Mass Destruction Commission, *Weapons of Terror: Freeing the World of Nuclear, Biological and Chemical Arms* (Stockholm: EO Grafiska, 2006).

58 International Commission on Nuclear Non-proliferation and Disarmament, *Eliminating Nuclear Threats: A Practical Agenda for Global Policymakers* (Canberra: Paragon, 2009), p. 15.

59 Steven Starr, "Catastrophic Climatic Consequences of Nuclear Conflict," *INESAP Bulletin*, no. 28 (April 2008).

a challenge for the future in the 1980s. In turn, significant progress was made in research on the climate effects of localized limited nuclear war and on the occurrence of food crises.

With respect to the underlying situation, it cannot be ignored that global warming emerged as an important political agenda from the late 1980s through the 1990s. In particular, the Intergovernmental Panel on Climate Change (IPCC), established in 1988, assessed studies of the climate effects of greenhouse gases by global researchers, which led to the entry into force of the United Nations Framework Convention on Climate Change (UNFCCC) in 1994. The connection in research methodology between research on the climate effects of nuclear war and research on global warming has long been noted, as evidenced by the term "Anthropocene"—the geological epoch when human activities began to affect the global environment—proposed by Crutzen, who earlier pioneered the study of nuclear winter, and the use of climate models in research.[60] In addition, the possession of nuclear weapons by India and Pakistan, as well as concerns generated by the Kargil conflict over limited nuclear war between these two countries,[61] have provided a new direction for the study of nuclear winter in the hypothetical nuclear war scenario.

For example, in 2007, Alan Robock et al. used ModelE, a global climate model developed by the NASA Goddard Institute for Space Studies (GISS), to calculate the response of the climate system to a regional nuclear war caused by emerging nuclear weapon states. The study assumes 100 nuclear bombs with a yield similar to that of the nuclear bomb dropped on Hiroshima are used to attack cities in the subtropical zone. It revealed that, while the climate effects would not be as enormous as those of a hypothetical U.S.-Soviet/U.S.-Russia nuclear war, climate changes would be large and long-lasting. Specifically, modern cities would have high fuel loadings, and the subtropical climate would heat the smoke and loft it into the high stratosphere. Robock et al. also found that years of surface cooling and precipitation reductions after limited nuclear war would affect food supplies.[62] The study was groundbreaking in that it was one of the earliest simulations to use a modern, comprehensive atmosphere-ocean coupled climate model, and it employed a scenario with nuclear proliferation in South Asia in mind. Of further note is that the study was well timed, coinciding with the aforementioned assessments of nuclear winter studies using climate models in the ICNND report.

In 2014, Michael J. Mills et al. analyzed global cooling and ozone loss during the several decades following nuclear war. They employed a nuclear war scenario in which small nuclear warheads of the same size as those dropped on Hiroshima and Nagasaki are used locally. They found that the detonation of 50 nuclear warheads with a yield of 15 kilotons would produce 5 teragrams of black carbon, which would rise to the stratosphere and spread globally, resulting in surface temperature drops and stratospheric temperature increases. Using the Whole Atmosphere Community Climate Model (WACCM) with an e-folding time of 8.7 years compared to the 4 to 6.5-year span for previous studies, Mills et al. discuss the possibility of ozone losses of 20 to 50% over populated areas and surface temperature decreases of an unprecedented scale in the

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60 Eglė Rindzevičiūtė, *The Power of Systems: How Policy Sciences Opened Up the Cold War World* (Ithaca: Cornell University Press, 2016), p. 152.

61 Ashley J. Tellis, C. Christine Fair, and Jamison Jo Medby, *Limited Conflicts under the Nuclear Umbrella: Indian and Pakistani Lessons from the Kargil Crisis* (Santa Monica: RAND Corporation, 2001), p. 15.

62 Alan Robock et al., "Climatic Consequences of Regional Nuclear Conflicts," *Atmospheric Chemistry and Physics*, no. 7 (April 19, 2007), p. 2003.

last 1,000 years. Ozone depletion would increase summer UV indices in mid-latitude regions by 30–80%, causing widespread damage to human health, agriculture, and terrestrial and aquatic ecosystems. Extreme cooling from reduced sunlight would shorten the growing season for crops by 10 to 40 days per year for five years after nuclear war. Mills et al. also note the risk of a nuclear famine, stating that global food production would be severely impacted by the reduction of surface temperatures for more than 25 years after nuclear war due to thermal inertia, albedo effects in the ocean, and expanded sea ice, as well as by resulting temperature drops and enhanced UV.[63]

Many of the nuclear winter case studies in the 1980s assumed the use of nuclear weapons with a total yield of several thousand megatons, and discussed the environmental and climatic transformations that survivors would face after nuclear war. While some previous studies touched on the risk of nuclear famine as mentioned above, Robock et al. presented an alternative nuclear famine theory, which predicted that even a limited nuclear war using nuclear assets with a lower yield would have a significant impact on global food supplies. This new nuclear famine theory has continued to be studied employing climate models. For example, a 2015 paper by Lili Xia et al. warns of the risk of transboundary nuclear famine, explaining that a limited nuclear war in South Asia would have serious spillover effects on food production in the grain belt of China.[64]

In 2018, Joshua M. Pearce and David C. Denkenberger assessed the lower limit of nuclear weapon quantities for achieving limited nuclear war—a nuclear war whose climate impacts would not be lethal. They also assessed the ability of nations at war to feed themselves without relying on imports if a nuclear war results in "nuclear autumn," which Pearce and Denkenberger define as 10% global agricultural shortfall, and analyzed food shortages and economic impacts separately under three nuclear war scenarios in which 7,000, 1,000, or 100 nuclear weapons are used.[65] In 2019, Joshua Coupe et al. introduced a more sophisticated stratospheric chemistry approach to simulate the global environment in the aftermath of nuclear war. Recognizing that the greatest uncertainty associated with calculating the climate impact of nuclear war is the number of nuclear weapons used, their yields, and the targets chosen for nuclear attack, Coupe et al. employed a scenario using all nuclear forces that are within the deployment limits set by existing U.S.-Russia nuclear arms control treaties. They simulated that soot aerosols would be emitted over the United States and Russia, based on the estimate that 150 teragram of black carbon would be emitted into the upper troposphere in a nuclear war. They then compared the latest WACCM4 global climate model (a full stratospheric chemistry and atmospheric aerosol radiation model for dust particle growth with a 2° horizontal resolution and 66 layers from the surface to 140 km) and ModelE used by Robock et al. in 2007 (a simulation with 4° × 5° horizontal resolution and 23 layers from the surface to 80 km) in simulating the climatic effects of nuclear war under the same conditions. In both climate models they found that the dust rising into the stratosphere blocked sunlight, causing temperatures to drop to below zero in the Northern Hemisphere even during the summer. The WACCM4 calculation showed a faster disappearance of smoke compared to the ModelE

[63] Michael J. Mills et al., "Multidecadal Global Cooling and Unprecedented Ozone Loss Following a Regional Nuclear Conflict," *AGU Earth's Future*, vol. 2, no. 4 (April 2014), pp. 161–176.

[64] Lili Xia et al., "Decadal Reduction of Chinese Agriculture after a Regional Nuclear War," *AGU Earth's Future*, vol. 3, no. 2 (February 2015), pp. 37–48.

[65] Joshua M. Pearce and David C. Denkenberger, "A National Pragmatic Safety Limit for Nuclear Weapon Quantities," *Safety*, vol. 4, no. 25 (2018), pp. 1–17.

calculation and no significant change in climate impact. On the other hand, the 150 teragram of soot generated by a hypothetical nuclear explosion had a greater impact on surface temperatures and led to more pronounced precipitation reductions in WACCM4 than ModelE.[66]

The nuclear famine theory that employs climate models was not without opposition. In 2018, Jon Reisner et al. from the Los Alamos National Laboratory in the United States criticized the 2007 paper by Robock et al. by using numerical models to calculate the effects of firestorm, showing that black carbon would not reach the upper atmosphere and climate effects of nuclear war would be negligible.[67] A debate between Reisner et al. and Robock et al. took place in an academic journal through 2019.[68] That same year, Toon, Robock, Xia et al. published a paper in *Science Advances* which reflects the recent nuclear proliferation situation and presents research findings that update the nuclear famine theory. The paper uses a scenario in which Pakistan and India launch a nuclear attack on each other's urban areas with 150 and 100 nuclear weapons, respectively. The calculations revealed that, after nuclear war, surface temperatures would drop by 2–5°C, precipitation would be reduced by 15–30%, and sunlight would decrease by 20–35%, which would seriously impair food production and cause mass starvation, resulting in collateral fatalities around the world.[69]

In their 2021 paper, Coupe et al. examined the climate impacts of smoke from fires started by nuclear war, with a focus on elucidating the physical and biological state of the post-nuclear war oceans. Using an Earth system model, they simulated six scenarios: (1) U.S.-Russia nuclear war (100–500 kt yield, 3,100–4,400 nuclear weapons); (2) type 1 India-Pakistan nuclear war (100 kt yield, 500 nuclear weapons); (3) type 2 India-Pakistan nuclear war (100 kt yield, 250 nuclear weapons); (4) type 3 India-Pakistan nuclear war (50 kt yield, 250 nuclear weapons); (5) type 4 India-Pakistan nuclear war (15 kt yield, 250 nuclear weapons); and (6) type 5 India-Pakistan nuclear war (15 kt yield, 44 nuclear weapons). They showed that global cooling would cause a large, sustained response in the equatorial Pacific similar to an El Niño persisting for up to seven years. This "Nuclear Niño" would be characterized by westerly trade wind anomalies and a shutdown of upwelling in the equatorial Pacific, caused primarily by cooling of the Maritime Continent and tropical Africa. The paper suggests that decrease in sunlight and changes in ocean circulation would cause a 40% reduction in equatorial Pacific phytoplankton productivity, which would result in extreme climate change that could not only lead to crop failure but also seriously undermine global food security.[70]

Although research on the nuclear winter theory since the 2000s made advances with the

66 Joshua Coupe et al., "Nuclear Winter Responses to Nuclear War between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE," *JGR Atmospheres*, vol. 124, no. 15 (August 16, 2019), p. 8524, 8541.

67 Jon Reisner et al., "Climate Impact of a Regional Nuclear Weapons Exchange: An Improved Assessment Based on Detailed Source Calculations," *JGR Atmospheres*, no. 123 (2018), p. 2752.

68 Alan Robock, Owen B. Toon, and Charles G. Bardeen, "Comment on 'Climate Impact of a Regional Nuclear Weapon Exchange: An Improved Assessment Based on Detailed Source Calculations' by Reisner et al.," *JGR Atmospheres*, no. 124 (2019), p. 12953.

69 Owen B. Toon, Charles G. Bardeen, Alan Robock, Lili Xia, Hans Kristensen, Matthew McKinzie et al., "Rapidly Expanding Nuclear Arsenals in Pakistan and India Portend Regional and Global Catastrophe," *Science Advances*, vol. 5, no. 10 (October 2, 2019), p. 1.

70 Joshua Coupe et al., "Nuclear Niño Response Observed in Simulations of Nuclear War Scenarios," *Communications Earth & Environment*, vol. 2, no. 18 (2021), pp. 1–3.

refinement of climate models, it has not attracted the same attention from the media and the public as it did in the 1980s. There are various possible reasons for this. One is that the initial research assumed a limited nuclear war among emerging nuclear weapon states. Therefore, Western nations did not consider nuclear risk as an imminent issue, and the research failed to generate political interest. Furthermore, nuclear war may have become a waning possibility or concern, with more than a quarter century having passed since the end of the Cold War. This trend, however, is beginning to change. In April 2021, the U.S. Congress mandated that the NAS conduct a study and assessment of the climate effects of nuclear war, particularly current models of nuclear explosions with respect to fires, atmospheric transport of gases from nuclear war-related explosions, and the consequences of soot and other particles on weather, agriculture, and long-term ecosystem viability.[71] The climate effects of nuclear war have traditionally been examined in academic journals using several nuclear war scenarios. Attention will be fixed on what conclusions the NAS will present in light of the recent debates. As research on nuclear famine provides new input for areas where scientific knowledge had been lacking since the 1980s, it is clear from the discussion thus far that the nuclear winter theory still has important implications for international security and nuclear deterrence.

Conclusion

When the nuclear winter theory emerged in the 1980s, the outbreak of a U.S.-Soviet nuclear war was a real concern for many people. Against this backdrop, Crutzen and Birks pioneered the study of the climate effects of nuclear war, and many researchers followed in their footsteps by publishing their own papers in peer-reviewed journals. Their numerous research findings, along with the theory of nuclear winter coined by TTAPS, have been described as a discourse that helped to end the Cold War and reduce nuclear arsenals. TTAPS took to the media to emphasize the risks of nuclear war and nuclear winter. Due to its political nature, however, the research aroused distrust and suspicions among some scientists. Although various debates transpired in academic journals, no definitive paper critical of the nuclear winter theory has yet been published. Conversely, since the start of the 21st century, the evolution of climate effect studies using advanced climate models has gradually provided new input for areas where scientific knowledge was insufficient. At this juncture, it is most important that the latest findings from nuclear winter studies be reevaluated from a security perspective.

As for the nature of this reassessment, George Perkovich, who contended that the end of the nuclear age will occur either through human annihilation in a nuclear war, including a nuclear winter, or through nuclear disarmament, proposed that the United States, Russia, China, India, and Pakistan conduct studies of the environmental, climate, and agricultural effects of nuclear war scenarios and disclose the results.[72] However, the latest trends in nuclear winter research reviewed in this paper suggest that doing so is no longer necessarily adequate. Attention should be given to the climate effects of limited nuclear war and the risk of nuclear famine that does not affect the nations at war exclusively. To this end, there is a need for an international framework that can

71 Daryl G. Kimball, "Congress Mandates Studies on Nuclear War," *Arms Control Today*, vol. 51, no. 3 (April 2021), p. 33.

72 George Perkovich, "75 Years On, How Will the Nuclear Age End?" War on the Rocks, August 6, 2020, https://warontherocks.com/2020/08/75-years-on-how-will-the-nuclear-age-end/.

compile and evaluate the latest nuclear winter studies from a neutral standpoint, equivalent to the role of the IPCC in climate change initiatives. In addition, a scientific study of the climate effects of nuclear war participated by experts from all nuclear weapon states is essentially necessary. The study should ideally scrutinize not only limited nuclear war but also the possibility of escalation. It may be time to review the conventional approach to nuclear risk, based around the reassessment of the studies of nuclear war's climatic effects.

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