WHATEVER HAPPENED TO NUCLEAR WINTER?

National Security Report

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Summary

In 1983, Turco, Toon, Ackerman, Pollack, and Sagan (TTAPS) published "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions" in *Science* magazine, launching a fierce debate among scientists and policymakers for the remainder of the decade. Through modeling various nuclear exchange scenarios between the Soviet Union and the United States, TTAPS concluded that the sooty smoke produced from fires and lofted into the stratosphere could dramatically reduce the average temperature over large portions of Earth's surface for months, thereby plunging the world into a "nuclear winter." After the intense attention in the 1980s, the nuclear winter debate and scientific research largely died down after the end of the Cold War. Scientific study was rekindled and refocused in the 2000s amid concerns about the nuclear risk associated with the growing arsenals of India and Pakistan. However, despite the significant climatic consequences predicted by these regional nuclear exchange studies, based on publicly available information, government interest in nuclear winter has remained low. We undertook a comprehensive literature review to (1) understand the evolution and current state of nuclear winter research and policy analysis; (2) understand the apparent loss of government interest since the end of the Cold War; and (3) assess alternative future courses of action. We find that while nuclear winter is potentially the most severe consequence of nuclear war, the science is still fraught with uncertainties that have undermined its acceptance. The initial widespread interest waned because of a combination of factors, principally the end of the Cold War but also the impracticality of policy solutions and the problematic mixture of science and politics. We recommend renewed consideration of nuclear winter in policy formulation and a sustained research program to reduce uncertainties.

Introduction

In the aftermath of the 1945 bombings of Hiroshima and Nagasaki, many of the immediate catastrophic consequences of nuclear weapons were made clear to the world. Yet, in 1983, a study published in *Science* magazine argued we had been ignorant of perhaps the most severe consequence of a nuclear exchange.[1] In that study, authors Turco, Toon, Ackerman, Pollack, and Sagan (hereinafter TTAPS) concluded that there would also be global catastrophic climatic consequences in a variety of nuclear exchange scenarios. They argued that, in these scenarios, the sooty smoke produced from fires would be lofted into the stratosphere, where it would spread out across the Northern and Southern Hemispheres, attenuating sunlight and causing global surface temperatures to plummet for months. This "nuclear winter" effect would impact not only the countries involved in a nuclear exchange but noncombatant countries as well.

The TTAPS paper sparked a fierce debate in both the science and policy communities for the remainder of the 1980s. During this period, numerous published scientific papers expanded on the initial research of the TTAPS group. While many of these publications also predicted a large climatic impact following a nuclear exchange, others predicted a much smaller effect. Because of these variations in results, which are partially attributable to disparities in study assumptions, as well as underdevelopment of models and large uncertainties in model parameters, doubt was cast over the more extreme nuclear winter predictions.

Despite significant skepticism in the scientific research, the policy community paid serious attention to TTAPS's and others' findings. Several congressional hearings[2] explored the long-term impacts of a nuclear exchange, and Congress ordered the Department of Defense to review the nuclear winter research and produce an assessment. The department's report, delivered in 1985, asserted that "the issues raised by the possibility of effects of nuclear war on the atmosphere and climate only strengthen the basic imperative of US national security policy—that nuclear war must be prevented."[3] The report went on to caution that "there are those who argue, in effect, that we no longer need to maintain deterrence as assiduously as we have, because the positive prospect of catastrophic climatic effects would themselves deter Soviet leadership from attack. We strongly disagree, and believe that we cannot lower our standards for deterrence because of any such hope."[4] The report further advanced that "this entire area of consideration—the impact of possible climatic effects on deterrence—is made more complex by the fact that it relates to what the Soviets understand about such climatic effects and how that understanding would influence their behavior in a crisis situation. We will probably never have certainty of either; indeed, we cannot know the latter before the event, and knowing the former is made difficult by their behavior so far, which has been to mirror back to us our own technical analysis and to exploit the matter for propaganda."[5]

By the end of the Cold War in 1991, research on nuclear winter had all but died. A few scientific studies were published in the early 1990s, and although those studies expanded on the initial nuclear winter research, conversation on the broader stage diminished. It wasn't until 2007 that a group of scientists reinvigorated the nuclear winter debate by publishing articles detailing the global impacts of a "small" regional exchange between the newly nuclear countries India and Pakistan.[6] These

1 Turco et al., "Nuclear Winter."

2 *Climatic, Biological, and Strategic Effects of Nuclear War*; and *Nuclear Winter: Joint Hearing*.

3 DOD, "Potential Effects," 172.

4 DOD, "Potential Effects," 172.

5 DOD, "Potential Effects," 172–173.

6 Toon et al., "Atmospheric Effects and Societal Consequences"; and Robock et al., "Climatic Consequences."

papers sparked interest on the international stage, prompting studies out of Sweden and Switzerland, as well as a studies by Los Alamos National Laboratory[7] and Lawrence Livermore National Laboratory.[8] While most of these new studies predicted global-level impacts from even a small nuclear exchange, the Los Alamos study found negligible climatic effects. In any event, despite these studies' newer emphasis on regional scenarios, which were thought to be more plausible, the science remains unresolved, and publicized political interest in nuclear winter has remained low to the present day.

To better understand nuclear winter phenomenology and the evolution of the nuclear winter debate, we reviewed and analyzed scientific studies, policy papers, and government reports. We attempted to include all comprehensive scientific studies through 2020, which we define as those that model a full exchange scenario from black carbon injection through to climatic impacts. We did not include reviews, or analyses, of individual model parameter studies or studies focused on a single climatic impact, such as ozone loss. In addition to these scientific studies, we reviewed and analyzed selected policy papers on nuclear winter. The policy papers range from short commentaries to transcripts of congressional hearings dedicated to nuclear winter. We did not search for, and are unaware of, any significant classified studies or policy papers on nuclear winter, but we did include formerly classified reports that have been released through the Freedom of Information Act.[9] Finally, we did not capture literature associated with public interpretation of nuclear winter, such as newspaper articles, leaving the response of the general public open for future analysis.

We begin this paper by discussing the science of how a nuclear exchange could affect the climate, breaking down the phenomenon of nuclear winter into constituent processes and detailing each process. We then look at the evolution of nuclear winter research and policy from its beginnings to the most recent studies. Given this scientific and historical context, we consider several hypotheses for the apparent waning government and public interest starting near the end of the Cold War and continuing to the present day. We culminate our analysis with an exploration of alternative future paths for nuclear winter research and nuclear weapons policy. Our main conclusions are:

- Nuclear winter is potentially the most severe consequence of nuclear war, but the science remains fraught with uncertainties.
- Initial widespread interest waned because of a combination of factors, principally the end of the Cold War but also the impracticality of policy solutions, the problematic mixture of science and politics, and difficulties in resolving scientific uncertainties.
- With increased proliferation and increasing concern about the nuclear threats from Russia and China, the science and policy implications of nuclear winter need to be addressed anew.

We end with our own perspectives on the nuclear winter debate. We hope that this paper will help renew interest in nuclear winter and motivate further research by both the government and the private sector.

Nuclear Winter Science and Phenomenology

The idea that nuclear weapons could affect the atmosphere was first hypothesized during the early stages of the Manhattan Project when Edward Teller raised the concern that the intense heat from nuclear fission could ignite (fuse) nitrogen in the atmosphere in a chain reaction that would envelop the planet. Since then, scientists have investigated

7 Reisner et al., "Climate Impact."

8 Wagman et al., "Examining the Climate Effects."

9 Lunn, "Global Effects of Nuclear War."

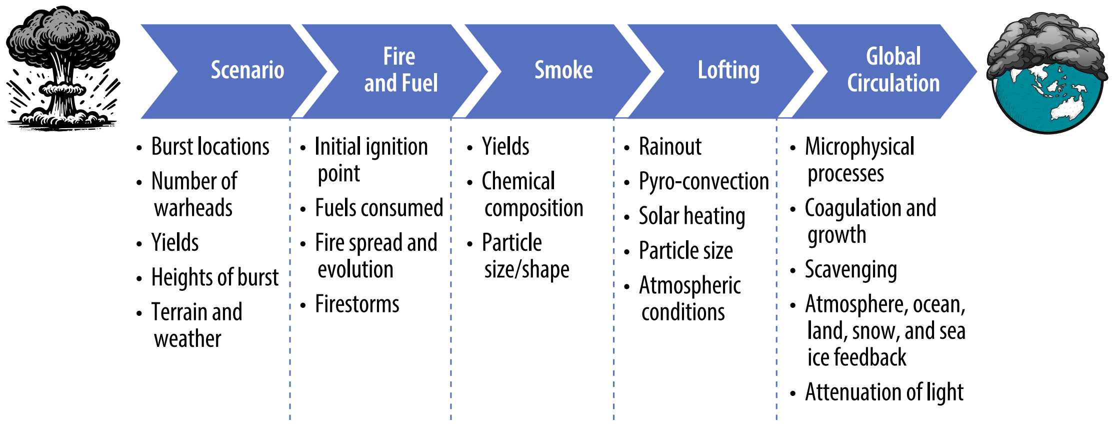


Figure 1. Sequence of Phenomena Leading to Nuclear Winter

atmospheric nuclear weapons effects, including radioactive fallout, electromagnetic pulse, ozone depletion, and sunlight obscuration from the lofting of dust particles. The effects of smoke from fires ignited during a large nuclear exchange were first investigated in the 1982 paper by Crutzen and Birks.[10] Although the paper did not address temperature reduction, it was the first to outline the atmospheric effects of smoke from fires ignited by nuclear weapons, and it provided a starting point for the research that would follow over the next decades.

Fortunately, the atmospheric consequences of the fires ignited from a large nuclear exchange have not been empirically determined and cannot be directly tested. Because of this, scientists are forced to rely on inexact knowledge of nuclear weapon effects and a theoretical understanding of the atmospheric response. The resulting atmospheric behavior is determined by decomposing the problem into constituent, dynamically intertwined, processes. Each process and the interactions among processes are then analyzed using a combination of scientific theory, modeling and simulation, and observation and understanding of analogous phenomena.

In this section, we provide an overview of the phenomenology of nuclear winter, written for the scientifically literate reader, although not necessarily for climate or atmospheric scientists. We hope to make clear that the science is both complicated and unsettled. While it is most appropriate to use the term *nuclear winter* to describe only a significant surface temperature reduction, for brevity, we apply this term broadly to include the recent findings of modest temperature reductions.

Figure 1 shows our decomposition of the processes that result in global climatic consequences. Major elements include the exchange scenario, the amounts and types of fuel that will burn, the amounts and types of smoke aerosols[11] that are produced, how the smoke will be lofted into the atmosphere, and how the smoke will circulate globally. The parameters shown in the figure stop at climatic impacts and do not account for societal impacts.[12]

10 Crutzen and Birks, "Atmosphere after a Nuclear War."

11 Aerosols are a suspension of particulate matter in gas.

12 The societal impacts due to the widespread atmospheric consequences of a nuclear exchange are an ongoing and rapidly expanding area of research but are beyond the scope of this work. A recent grant from Open Philanthropy (Robock and Toon, "Environmental and Human Impacts") has resulted in many published works on ecological, environmental, and societal impacts, including ocean state (Harrison et al., "A New Ocean State"; and Coupe et al., "Nuclear Niño Response") and acidification (Lovenduski et al., "Potential Impact of Nuclear Conflict"), food security (Jägermeyr et al., "A Regional Nuclear Conflict"; Scherrer et al., "Marine Wild-Capture Fisheries"; and Xia et al., "Global Food Insecurity and Famine"), and the economy (Hochman et al., "Economic Incentives").

Scenarios

Nuclear exchange scenarios define key parameters of the hypothetical nuclear exchange under study. Scenario parameters include the numbers and yields of weapons detonated, the timeline of detonations, weapons' thermal outputs and heights of burst, and locations targeted. Multiple processes within the nuclear winter calculation are dependent on the scenario parameters, including the quantity and nature of combustible material in the environs and local weather and topography.

Nuclear winter studies vary significantly in the level of scenario detail they provide. At one extreme, some studies provide detailed timelines of events, weapon yields and heights of burst, and specific target locations.[13] At the other extreme are studies that omit scenario descriptions entirely and start with postulated smoke injection into the atmosphere based on previous nuclear winter studies. Many studies lie somewhere between these extremes, providing some information on numbers and yields of weapons and general regions targeted but omitting many details, such as specific targeted locations, weather, and topography. The wide variation in detail and the often missing information on scenario assumptions makes comparing results across studies challenging.

Scenarios considered in nuclear winter studies can be split into two categories: studies primarily conducted during the Cold War investigating large nuclear exchanges between the United States and the Soviet Union/Russia and more recent studies exploring a smaller "regional" nuclear war between India and Pakistan. We are unaware of nuclear winter studies that focus on bilateral conflicts between other nuclear states, multilateral conflicts, or conflicts between nuclear and nonnuclear states.

[13] Example studies that include detailed scenarios are Turco et al., "Nuclear Winter"; Toon et al., "Rapidly Expanding Nuclear Arsenals"; and Wagman et al., "Examining the Climate Effects."

Fire and Fuel

With the scenario parameters and knowledge of nuclear weapons effects, the amount of fuel burned as a result of each detonation can be calculated. Calculating the amount and character of material ultimately consumed as a result of the detonations and subsequent fire propagation requires input estimates of the area that is likely to ignite and the density distribution of the flammable materials over that area, as well as of topography and weather.

The number and distribution of ignition points as a result of a nuclear detonation are dependent on the thermal output from each nuclear fireball, the altitude of burst, local weather and terrain, and thermal radiation effects on materials. Weather and terrain may block or attenuate some of the outgoing thermal energy, and the thermal radiation effects on materials will determine which materials ignite.[14]

How a fire evolves from the initial ignition points is dependent on characteristics of the targeted location, including the abundance of fuel, types of fuel, fuel moisture, and atmospheric conditions, such as temperature, moisture, wind, and stability. These parameters affect fire dynamics, including spread and the percent of burnable fuel that is consumed.[15] For example, some types of fuel, such as ruptured gas lines and ignited oil and gas reserves, will greatly increase the spread and intensity (energy released per unit area) of the fires, while fire breaks and rubble from collapsed buildings can snuff out fires.

The amount and types of fuel consumed by fires, including both natural fuels and those from the built environment, will impact the amount and composition of smoke. Natural fuels include vegetation, such as forests and grasslands, and the fuels from the built environment include infrastructure, such as buildings, the materials within those buildings, and oil and gas reserves. The fuels available

[14] National Research Council, *Effects on the Atmosphere*.

[15] National Research Council, *Effects on the Atmosphere*.

will differ for each targeted location and will vary especially when comparing dense urban environments with isolated military installations.

Under certain meteorological conditions, a firestorm—"a mass fire in which there is a large central convective core into which street level winds flow from all directions"[16]— could develop. Firestorms impact fire dynamics and the amount of fuel consumed but, most importantly, the amount of smoke lofted into the stratosphere. They are more likely to occur in very intense localized fires and under conditions of light or no wind and flat terrain. The inward blowing winds will limit fire spread, but burnable fuel within the firestorm will be completely consumed.

Nuclear winter studies have varied significantly in their approaches, level of detail, and assumptions when determining the amount of fuel consumed. Some studies have taken a detailed approach leveraging complex models of nuclear weapon effects and fire evolution (spread, duration, and intensity),[17] while many other studies have relied on simple assumptions on the area burned and the fraction of fuel consumed based on historical fires.[18]

To estimate the amount of fuel in an area, several studies assumed a direct relationship between the quantity of fuel available and the local population density.[19] They derived the relationship by using information from surveys of land use and combustible materials.[20] These surveys determine the amounts and types of materials (wood/lumber, petroleum products, plastics/polymers, asphalt, cloth, food, etc.) as a function of population density. Authors of other nuclear winter papers determined fuel loading through extensive surveys of the combustible materials in particular regions and cities.[21] The nominal amount of fuel per person and the amount of combustible materials are expected to vary geographically but are uncertain and difficult to measure.

Smoke

The yield and composition of smoke emitted from a fire is dependent on the total amount of fuel consumed, the relative abundance of different types of fuels consumed, fire intensity, and weather.

Burning different types of fuels, such as wood, paper, plastics, cloth, petroleum, or vegetation, produces varying amounts and compositions of emissions. Smoke includes black carbon and organic aerosols, which contain carbon and other elements. Fires can produce smoke with a wide range of black carbon and organic aerosol ratios, and these composition differences impact the optical properties of the emissions, lofting height, and residence times in the atmosphere. Once produced, smoke emissions may coagulate, creating larger particles. This further changes their optical properties and likelihood of removal from the atmosphere through precipitation scavenging.

16 Wagman et al., "Examining the Climate Effects."

17 Robock, "Snow and Ice Feedbacks"; Covey, Schneider, and Thompson, "Global Atmospheric Effects"; MacCracken and Walton, "Effects of Interactive Transport and Scavenging"; Thompson, "Global Interactive Transport Simulations"; Malone et al., "Nuclear Winter"; Ghan, MacCracken, and Walton, "Climatic Response"; Pittock, Walsh, and Frederiksen, "General Circulation Model Simulation"; Ghan, "Chronic Climatic Effects"; Robock et al, "Nuclear Winter Revisited"; Mills et al., "Multidecadal Global Cooling"; and Pausata et al., "Climate Effects."

18 Crutzen and Birks, "Atmosphere after a Nuclear War"; Turco et al., "Nuclear Winter"; and Crutzen, Galbally, and Brühl, "Atmospheric Effects," estimated the amount of forest that would burn based on historical fires and estimated fuels available in forests. Toon et al., "Atmospheric Effects and Societal Consequences"; Stenke et al., "Climate and Chemistry Effects"; and Toon et al., "Rapidly Expanding Nuclear Arsenals," all assumed that an area of thirteen square kilometers would burn per detonation, based on the Hiroshima bombing.

19 Toon et al., "Atmospheric Effects and Societal Consequences"; Stenke et al., "Climate and Chemistry Effects"; and Toon et al., "Rapidly Expanding Nuclear Arsenals."

20 Small, Bush, and Dore, "Initial Smoke Distribution."

21 Reisner et al., "Climate Impact."

To arrive at assumptions about smoke emission yields and composition, most nuclear winter studies used information from historical fires[22] or surveys on yields and composition of smoke emitted when burning various materials.[23] More recent papers have described the use of advanced modeling techniques that calculate these parameters as part of complex fire simulations.[24] Almost all these studies have considered only black carbon in their calculations, under the assumption that organic aerosols would be destroyed by photochemical reactions in the stratosphere.[25] However, two relatively recent studies also included the role of particulate organic matter, which is a composition of organic carbon and associated chemical elements, in their calculations.[26]

Fire intensity also affects smoke production. As the scale of a fire increases, the fire tends to intensify, especially if given large quantities of fuel to burn. This intensification may reduce smoke emissions through several mechanisms, such as increased ventilation from induced turbulence and scavenging through induced precipitation.[27] While intense fires tend to produce less smoke overall, the smoke they produce is enriched in graphitic carbon, creating soot, which is more effective at absorbing light.[28]

Finally, under certain weather conditions, low-altitude precipitation will remove emissions as they are lofted, before they reach high altitudes. Once the soot is lofted above the tropopause, wet removal becomes very inefficient and the smoke will reside in the atmosphere for longer periods of time. Most early studies relied on observations of historical fires to estimate the fraction of smoke scavenged as a result of this mechanism. However, many newer studies included low-altitude scavenging in the models they used to estimate fire dynamics and atmospheric chemistry.[29]

Lofting

Once smoke aerosols are produced, their amounts and properties, as well as the atmospheric conditions, will determine how high they are lofted into the atmosphere. Numerous variables, such as winds, temperature inversions, humidity, and burning rate, impact the fire plume height.

While some of the smoke will be scavenged (removed) from the atmosphere through precipitation as water droplets condense on aerosol molecules, the remaining smoke aerosols will loft into the atmosphere through pyro-convection. Lofting by pyro-convection has been observed in forest fires above large combustion zones and has been modeled in simulations. It has been found that the height of the smoke plume is dependent on the intensity of the fires and is therefore dependent on the amount of available fuel and whether a firestorm or conflagration[30] develops.

In addition to experiencing pyro-convection, the smoke is expected to continue to loft higher into the upper troposphere or lower stratosphere through solar heating. There is observational evidence that vertical motion of smoke particles can be induced through the absorption of shortwave radiation. This process is still poorly understood but is expected to be dependent on particle size and atmospheric properties.

22 Crutzen and Birks, "Atmosphere after a Nuclear War"; and Turco et al., "Nuclear Winter."

23 Crutzen, Galbally, and Brühl, "Atmospheric Effects"; and Toon et al., "Atmospheric Effects and Societal Consequences."

24 Reisner et al., "Climate Impact"; and Wagman et al., "Examining the Climate Effects."

25 Wagman et al., "Examining the Climate Effects."

26 Pausata et al., "Climate Effects"; and Wagman et al., "Examining the Climate Effects."

27 National Research Council, *Effects on the Atmosphere*.

28 National Research Council, *Effects on the Atmosphere*.

29 Mills et al., "Multidecadal Global Cooling"; Reisner et al., "Climate Impact"; Toon et al., "Rapidly Expanding Nuclear Arsenals"; and Wagman et al., "Examining the Climate Effects."

30 A conflagration is a "raging destructive fire. Often used to denote such a fire with a moving front as distinguished from a fire storm" (NWS, *Fire Weather Glossary*).

One of the most variable parameters across nuclear winter studies is the altitude at which smoke is injected into the atmosphere. Early studies assumed that the smoke is uniformly distributed between the ground and nine to eleven kilometers in altitude.[31] Later studies assumed uniform distribution of smoke in the upper troposphere and then modeled the rise into the stratosphere.[32] More recent studies have calculated lofting as part of fire models.[33]

Global Circulation

Smoke aerosols that are lofted into the stratosphere are expected to reside in the atmosphere for long periods of time and to spread over large areas, attenuating the solar radiation reaching Earth's surface. The vertical and horizontal transportation and removal of aerosol particles, as well as the temporal evolution of the smoke throughout the atmosphere, are determined using complex climate and atmospheric models.

While the earliest nuclear winter studies used relatively simple one- or two-dimensional models to calculate the transportation and evolution of smoke aerosols in the atmosphere, the complexity of the models rapidly increased through the 1980s. The current state of the art involves fully coupled global climate models, which are those that include interactive ocean, land, sea ice, and atmospheric components. Modern models have variable vertical resolution and high horizontal spatial and temporal resolution. These global climate models are coupled with aerosol and radiation models for microphysics calculations of the dynamics of aerosol particles and their direct effect on solar radiation. Microphysics models and radiative-convective models predict the temporal evolution of smoke clouds, calculate smoke particle size distribution, and determine optical properties. From these calculations, the light fluxes and air temperatures as a function of time, location, and altitude can be calculated.

Temperature Reduction and Other Results

The TTAPS paper analyzed a spectrum of US–Soviet Union nuclear exchange scenarios. For most of these scenarios, this study predicted severe land temperature decreases for prolonged periods of time, with subfreezing temperatures persisting in the Northern Hemisphere for months and a significant decline in precipitation.[34] The authors generally acknowledged large uncertainties in their results, stemming from factors such as the limited number of nuclear exchange scenarios and simplistic fire, lofting, climate, and particle microphysics models. Throughout the Cold War, many other nuclear winter studies cited results consistent with these early predictions.[35] However, some papers found less severe temperature decreases, albeit with still very large uncertainties in their results.[36] In 2008, one study investigated a large exchange scenario, similar to those studied in the 1980s but with updated modeling tools. This study predicted a temperature decrease of seven to eight degrees Celsius persisting for years and a lingering four-degree decrease after a decade, as well as significant impacts on global precipitation.

[31] Covey, Schneider, and Thompson, "Global Atmospheric Effects"; MacCracken and Walton, "Effects of Interactive Transport and Scavenging"; and Thompson, "Global Interactive Transport Simulations."

[32] Robock et al., "Climatic Consequences"; Mills et al., "Multidecadal Global Cooling"; Pausata et al., "Climate Effects"; and Toon et al., "Rapidly Expanding Nuclear Arsenals."

[33] Reisner et al., "Climate Impact"; and Wagman et al., "Examining the Climate Effects."

[34] Turco et al., "Nuclear Winter."

[35] Robock, "Snow and Ice Feedbacks"; MacCracken and Walton, "Effects of Interactive Transport and Scavenging"; Thompson, "Global Interactive Transport Simulations"; and Malone et al., "Nuclear Winter."

[36] Covey, Schneider, and Thompson, "Global Atmospheric Effects"; Ghan, MacCracken, and Walton, "Climatic Response"; and Pittock, Walsh, and Frederiksen, "General Circulation Model Simulation."

The studies exploring exchange scenarios between India and Pakistan predicted less severe, but still significant, temperature, ozone, and precipitation reductions. The first paper that analyzed an India–Pakistan nuclear exchange found an average land temperature decrease of one to two degrees Celsius that would persist for years and a precipitation decrease of 10 percent.[37] Over the next several years, multiple studies explored similar exchange scenarios and predicted similar temperature and precipitation decreases.[38] Several of these studies also noted significant loss of the ozone layer.[39]

Current Debate and Uncertainties

In 2018, a group from Los Alamos National Laboratory published "Climate Impact of a Regional Nuclear Weapons Exchange: An Improved Assessment Based on Detailed Source Calculations."[40] This paper not only suggested the US government's renewed interest in this phenomena, but it also revealed significantly different results for the India–Pakistan regional nuclear war scenario than previous studies. Reisner et al.[41] concluded that the atmospheric and climatic consequences for a regional nuclear war were significantly less severe than previous studies predicted. In particular, Reisner et al. compared their results with those of Mills et al.,[42] who had claimed that the India–Pakistan exchange would cause global average surface temperatures to drop by approximately 1.1 degrees Celsius in the first year and continue to decrease for five years until reaching a maximum cooling of 1.6 degrees Celsius, in addition to significant stratospheric ozone loss. Mills et al. assessed that this climatic impact would cause devastating effects on vegetation, agriculture, and ecosystems. Despite using the same nuclear exchange scenario and the same climate models (CESM1) as Mills et al., Reisner et al. concluded that "while modest, statistically significant differences occur during the first few years, longer-term impacts are unlikely, regional in scope, and limited in scale. None of the simulations produced a nuclear winter effect."

The differences in the Mills et al. and Reisner et al. study results stem from the discrepancies in the vertical profile of fire emissions as they are lofted. In 2019, several of the authors on the Mills et al. paper published a response[43] to the Reisner et al. study. In this response, Robock, Toon, and Bardeen outlined their concerns that the fire modeled in the Reisner et al. paper was "not typical of the type of mass fire likely to result from a nuclear attack on densely populated cities in India and Pakistan and therefore their smoke estimate may significantly underestimate the amount of smoke likely to rise into the upper troposphere and lower stratosphere during a nuclear war." Primarily, the discrepancy arises from differences in the assumed fuel loading and whether a firestorm would develop.

The disagreement between the conclusions of these two studies inspired a second Department of Energy study, this one conducted by Lawrence Livermore National Laboratory researchers.[44] Wagman et al. used a piecewise modeling approach similar to the Reisner et al. approach, where the fires and the emissions' composition, lofting, and evolution in the atmosphere were all simulated with numerical models and integrated to estimate the climatic impact. Wagman et al. found that the emissions lofted to higher levels of the atmosphere

37 Robock et al., "Climatic Consequences."

38 Stenke et al., "Climate and Chemistry Effects"; Mills et al., "Multidecadal Global Cooling"; Pausata et al., "Climate Effects"; Toon et al., "Rapidly Expanding Nuclear Arsenals"; and Wagman et al., "Examining the Climate Effects."

39 Mills, et al., "Massive Global Ozone Loss"; Mills et al., "Multidecadal Global Cooling"; Stenke et al., "Climate and Chemistry Effects"; and Wagman et al., "Examining the Climate Effects."

40 Reisner et al., "Climate Impact."

41 Reisner et al., "Climate Impact."

42 Mills et al., "Multidecadal Global Cooling."

43 Robock, Toon, and Bardeen, "Comment."

44 Wagman et al., "Examining the Climate Effects."

than previous studies suggested, which resulted in a larger climatic response than Reisner et al. estimated. However, Wagman et al. found that the changes in the climate were shorter-lived than the Mills et al. study suggested. Wagman et al. also carried out several sensitivity studies, including investigations of the relationship between fuel loading and lofting height.

While the past several decades have seen significant progress on most pieces of the nuclear winter puzzle, discrepancies in the results of recent nuclear winter papers highlight the continued need for additional research on this topic. Sensitivity studies need to be conducted to understand how variations and uncertainties in model parameters impact results. Assumptions on which the various models are based, and assumptions about model input parameters, also need to be validated. In addition, some of the models are still underdeveloped for addressing particular aspects of the nuclear winter problem. Several key areas that need further exploration include:

- A wider range of plausible nuclear exchange scenarios
- Detailed assessments of local fuel loading and local meteorology and terrain of targeted locations
- Continued research on understanding urban fires, the causes of firestorms, and the emissions of such fires
- Sophisticated microphysics modeling of the emissions, including how they loft and interact with the atmosphere
- More complete atmospheric chemistry models
- Continued improvements to the global circulation and radiation models
- Additional studies to assess the climatic impact of particulate organic matter produced in large fires

Conclusions on Nuclear Winter Science and Phenomenology

Since the early 1980s, a wide variety of methodologies, assumptions, and models have been leveraged to understand and quantify the possible climatic effects of a nuclear exchange. However, given the current debate and uncertainties, it is clear that more research is needed. As we reviewed the nuclear winter literature, several key conclusions emerged. They are discussed in this section.

First, a wider variety of scenarios should be developed and leveraged in nuclear winter studies. The scenarios should be developed through discussions with government and Department of Defense stakeholders to ensure government buy-in. New scenarios should also include possible nuclear wars between NATO and Russia and between the United States and China, as well as limited nuclear wars outside of South Asia, including on the Korean Peninsula. Both counterforce and countervalue scenarios should also be considered, as well as plausible combinations.

Second, more work is needed to integrate modern models of nuclear weapon blast and thermal outputs, fire ignition points, fire dynamics and spread, fuel availability and consumption, smoke yield and composition, lofting, and initial scavenging into nuclear winter studies. The two Department of Energy national laboratory studies[45] are examples where modern understanding of these processes has been integrated. However, given the discrepancies in results, more research is clearly required. The two Department of Energy national laboratory studies also highlight the advantage of having a diverse community of researchers and organizations exploring this problem. Each piece of the nuclear winter puzzle is complex and requires specialized expertise. Studies should attempt to include subject-matter experts for each process to

[45] Reisner, "Climate Impact"; and Wagman et al., "Examining the Climate Effects."

more fully understand the climatic impacts of a nuclear exchange.

Third, additional work to collect and integrate information on targeted locations is needed. Given the limited budgets for previous nuclear winter studies, it is understandable that these studies made broad assumptions on local weather, topography, and fuel availability. However, because of the importance of this problem, funding should be allocated to conduct surveys of possible targeted locations, including parameters such as seasonal meteorology, topography, building and infrastructure location and composition, and vegetation. Modern remote sensing capabilities and classification algorithms could be leveraged to expedite or automate much of this process.

Most importantly, our literature review revealed that the nuclear winter problem is not resolved within the scientific community. There are still many outstanding areas to explore, new methods and models to integrate, and uncertainties to decrease.

Evolution of the Nuclear Winter Debate

With this background on the science and phenomenology of nuclear winter, we now turn to the evolution of the debate on the topic.

Although the 1983 TTAPS paper was the first to introduce the phenomena of nuclear winter, it was not the first study to look at the atmospheric and climatic impacts of a nuclear exchange. Previous studies explored radioactive fallout and changes to the photochemical regime of the atmosphere, such as ozone depletion. The direct precursor to TTAPS was the 1982 Crutzen and Birks[46] paper, which studied sunlight obscuration from smoke produced from fires ignited in a nuclear exchange. While previous studies on radioactive fallout and ozone depletion generally were not included in our analysis, the Crutzen and Birks paper is included because it is so closely related to the TTAPS study; a related paper by Martin from 1982 is also included. Figure 2 is a chronological histogram of the included literature. For the purpose of this analysis, the publications have been divided into two eras: the Cold War era (1982–1993) and the nuclear winter revival era (2007–2020).

As the figure shows, the number of nuclear winter publications rapidly peaked shortly after the introduction of TTAPS in 1983. The number of publications gradually, then more rapidly, declined over the next several years until it reached a steady state of one to two publications per year in 1987. By 1994, after the end of the Cold War, a lull in nuclear winter publications began and lasted until 2007, when what we call the nuclear winter revival era started. The following subsections describe the literature in both eras in greater detail and theorize as to why there was a lull between 1994 and 2006.

The Cold War Era

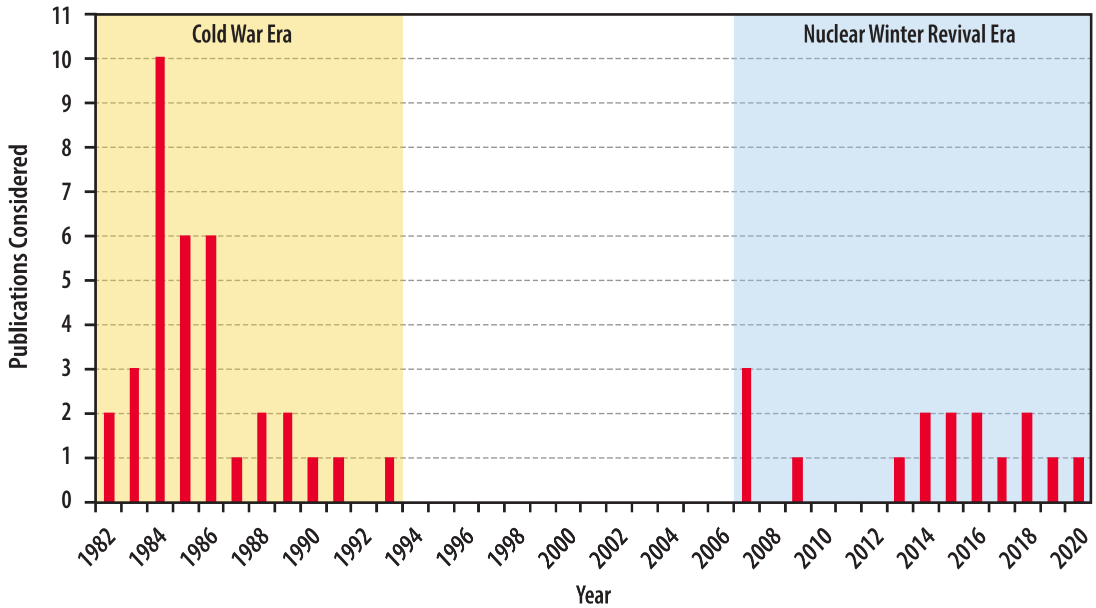
In 1982, Crutzen and Birks[47] published on the atmospheric effects of smoke produced by mass forest fires after a nuclear exchange and theorized on the impacts on the ozone layer and Northern Hemisphere agriculture. While they made no attempt to predict how the smoke would impact surface temperature, they concluded that famine and disease would plague all but a few survivors of a nuclear war.

This article set the stage for the first major comprehensive study of the climatic impacts of a nuclear war: the TTAPS paper.[48] As discussed earlier, this study concluded that a large strategic nuclear exchange between the United States and the USSR could severely reduce the surface temperature worldwide. The study's baseline scenario, a

[46] Crutzen and Birks, "Atmosphere after a Nuclear War."

[47] Crutzen and Birks, "Atmosphere after a Nuclear War."

[48] Turco et al., "Nuclear Winter."



Publications are split into two categories: the Cold War era and the nuclear winter revival era.

Figure 2. Number of Publications Considered over Time

five-thousand-megaton exchange, resulted in surface land temperatures of minus twenty degrees Celsius about one month after the exchange, with below-average temperatures lasting for three hundred days after the detonation. The TTAPS study was heavily criticized for being a one-dimensional calculation, for ignoring the role of feedback mechanisms, and for lacking accurate scavenging models.

Over the next eight years, scientists built on the foundations of the TTAPS study, leveraging more powerful computing resources and improving the climate models, incorporating increased horizontal resolution, vertical layers, snow/ice feedbacks, and scavenging. Eleven comprehensive studies were conducted by more than twenty-five researchers at institutions in the United States,[49] the USSR,[50] Germany,[51] and Australia.[52] These studies were supported by a variety of sources, including US government funding through the Defense Nuclear Agency, the Department of Energy, and the National Science Foundation.

Despite significant improvements in climate modeling, large uncertainties persisted in predicted average surface temperature reductions and precipitation losses. In addition, the choice of exchange scenario and starting assumptions likely played a significant factor in the variances across studies. Some papers started by specifying initial exchange scenarios with total yields varying between one hundred[53] and ten thousand megatons.[54] Many other studies, however, started with assumptions on the amount of smoke and the altitude(s) at which

49 Turco et al., "Nuclear Winter"; Robock, "Snow and Ice Feedbacks"; Covey, Schneider, and Thompson, "Global Atmospheric Effects"; MacCracken and Walton, "Effects of Interactive Transport and Scavenging"; Thompson, "Global Interactive Transport Simulations"; Malone et al., "Nuclear Winter"; Ghan, MacCracken, and Walton, "Climatic Response"; Turco et al., "Climate and Smoke"; and Ghan, "Chronic Climatic Effects."

50 Aleksandrov and Stenchikov, "Numerical Simulation."

51 Crutzen, Galbally, and Brühl, "Atmospheric Effects."

52 Pittock, Walsh, and Frederiksen, "General Circulation Model Simulation."

53 Turco et al., "Nuclear Winter"; and Robock, "Snow and Ice Feedbacks."

54 Turco et al., "Nuclear Winter"; and Robock, "Snow and Ice Feedbacks."

it was injected into the stratosphere.[55] Moreover, the studies did not provide the same output variables, making comparisons across studies difficult. While many subsequent studies found less drastic effects than TTAPS did, most still found significant global effects.

Throughout the Cold War era, scientists often concluded their publications with recommendations for nuclear policy changes they believed would help reduce the consequences of a nuclear exchange. This practice started with the early research on ozone depletion[56] and carried throughout the era. These policy recommendations included

- additional funding and research on nuclear winter;
- funding and research for studies to improve estimates of the likelihoods of various nuclear exchange scenarios;
- drastic reductions in global nuclear arsenals to a minimum deterrent level or complete disarmament;
- arms treaties prohibiting targeting of cities; and
- movement to low-yield or burrowing nuclear weapons.

Sagan was the most prolific in discussing the policy implications for nuclear winter, including articles in *Parade*[57] magazine and *Foreign Affairs*.[58] In these articles, he called for new treaties on yields and targeting, changes to first-strike policies and reliance on ballistic missile defense systems, relocation of silos, and, most importantly, significant reductions in arsenals below a nuclear winter "threshold"—the maximum number of nuclear weapons worldwide that, if exchanged, would not cause nuclear winter. Sagan estimated that this threshold would be between five hundred and two thousand nuclear warheads.[59] While the stockpile totals of the United States and Russia dwarfed the estimated nuclear winter threshold, Sagan reasoned that "for myself, I would far rather have a world in which the climatic catastrophe cannot happen, independent of the vicissitudes of leaders, institutions and machines. This seems to me elementary planetary hygiene, as well as elementary patriotism."[60]

In the years surrounding the emergence of the nuclear winter phenomena, government interest and activity on the topic was high. Even before the TTAPS results were revealed to the public, the US government had been supporting research on the atmospheric effects of nuclear war. Research included a National Academies of Sciences study[61] and a Lawrence Livermore National Laboratory study on ozone depletion, radiation, and atmospheric effects of nuclear war.[62] The government had also held congressional hearings in September 1982[63] in response to the Crutzen and Birks publication. After public release of the TTAPS paper, Sagan, other nuclear winter scientists, and those with dissenting views testified to the government a number of times, including in May and June 1984[64] and during congressional hearings in September 1984[65] and March 1985.[66] In 1985, Congress imposed a statutory mandate on the secretary

55 Covey, Schneider, and Thompson, "Global Atmospheric Effects"; MacCracken and Walton, "Effects of Interactive Transport and Scavenging"; Thompson, "Global Interactive Transport Simulations"; Malone et al., "Nuclear Winter"; Ghan, MacCracken, and Walton, "Climatic Response"; Pittock, Walsh, and Frederiksen, "General Circulation Model Simulation"; Turco et al., "Climate and Smoke"; and Ghan, "Chronic Climatic Effects."

56 Whitten, Borucki, and Turco, "Possible Ozone Depletions."

57 Sagan, "Nuclear Winter."

58 Sagan, "Nuclear War and Climatic Catastrophe."

59 Sagan, "Nuclear War and Climatic Catastrophe."

60 Sagan, "Nuclear War and Climatic Catastrophe."

61 National Research Council, *Effects on the Atmosphere*.

62 Teller, "Widespread After-Effects."

63 *Consequences of Nuclear War: Hearing*.

64 Rubinson, "Global Effects."

65 *Climatic, Biological, and Strategic Effects of Nuclear War*.

66 *Nuclear Winter: Joint Hearing*.

of defense to conduct a detailed review of the current scientific studies and the policy implications of nuclear winter and then requested that the report be redone in 1986.[67] Additionally, the General Accounting Office provided a report to Congress on uncertainties surrounding nuclear winter in 1986,[68] and the Foreign Relations Authorization Act for fiscal years 1986 and 1987 required that the United States engage in talks with the Soviet Union in joint studies on the atmospheric, climatic, environmental, and biological consequences of nuclear war.[69]

Amid this widespread government interest in nuclear winter, the topic quickly became contentious both within and outside of the government, with many disagreeing on the legitimacy of the research and the implications for nuclear deterrence policy and strategy. Some scientists, government officials, and policy advisers were critical of nuclear winter, citing large uncertainties and inaccuracies in the models and results. These opponents argued that it was too early to make nuclear deterrence policy and strategy changes because the science was immature. Others argued that the nuclear exchange scenarios explored in the nuclear winter papers were unrealistic and generally represented only worst-case scenarios. Still others dismissed the significance of the nuclear winter study findings and the implications for humanity as being just one more horrible consequence of nuclear weapons in a long list of horrible consequences.[70] Moreover, some scientists—Sagan in particular—were viewed as having an anti-nuclear-weapon agenda and using nuclear winter as just another tool to persuade the public to adopt their viewpoint. In general, uncertainty about the science and dislike of policy proposals motivated some people to embrace skepticism about nuclear winter science.

Another dynamic during the Cold War era was the uncertain Soviet buy-in on nuclear winter. The official Soviet party line was that nuclear winter had been adequately proved and would have disastrous consequences for all humankind.[71] However, some in the US government emphasized Central Intelligence Agency analysis that held that the Soviet Union was using nuclear winter as a tool for external political purposes.[72] As American political scientist Dr. Leon Goure testified during the 1984 congressional hearings on nuclear winter, "the only policy implication of nuclear winter cited by Soviet sources is the necessity to prevent a nuclear war and, consequently, the need for the United States to agree to all Soviet arms control proposals. There is no public indication that the possibility of a nuclear winter effect has in any way influenced current Soviet strategic doctrine or civil defense planning."[73]

Government officials used nuclear winter numerous times to support previously held convictions, as discussed earlier with respect to Sagan. In addition, the Soviet government cited nuclear winter to argue that the US concept of a limited nuclear war would still be devastating.[74] President Reagan used nuclear winter to justify the Strategic Defense Initiative.[75] And the 1985 Department of Defense report to Congress concluded that the "issues raised by the possibility of effects of nuclear war on the atmosphere and climate only strengthen the basic imperative of US national security policy—that nuclear war must be prevented."[76] So, despite the interest and seeming support scattered throughout the US and Soviet governments, it is unclear whether any

[67] Bowsner, *Nuclear Winter*.

[68] Bowsner, *Nuclear Winter*.

[69] Badash, *A Nuclear Winter's Tale*.

[70] Badash, *A Nuclear Winter's Tale*.

[71] Griffin, "Nuclear Winter and Nuclear Policy."

[72] *Nuclear Winter and Its Implications: Hearings*; and CIA, *Soviet Approach to Nuclear Winter*.

[73] *Nuclear Winter and Its Implications: Hearings*.

[74] Rubinson, "Global Effects."

[75] Rubinson, "Global Effects."

[76] Weinberger, "Potential Effects."

changes to nuclear policy or strategy were adopted as a result of nuclear winter considerations.[77]

By 1991, the Cold War ended and the Soviet Union dissolved into its constituent republics. It is particularly speculative to assert, as some nuclear winter scientists have, that considerations of nuclear winter were a major factor in ending the Cold War or in causing the subsequent large decline in the nuclear arsenals of the United States and Russia. In any event, there was a dramatic drop in the number of nuclear winter studies being conducted and a broader decline in interest in all things nuclear. Notwithstanding the decreased number of studies, research done in the early 1990s[78] addressed needed improvements to the 1980s-era models, such as longer simulations and coupled atmospheric and ocean models. The improved models still predicted dramatic climatic impacts, with results of average surface land temperature reductions varying between ten and twenty degrees Celsius.[79] These studies also predicted other environmental impacts, such as expanded sea ice coverage and ocean cooling (by as much as five degrees Celsius as late as twenty months after smoke injection), as well as the collapse of monsoons.[80]

By 1994, publication of significant nuclear winter papers essentially stopped. While the scientific and policy communities had disagreed about the magnitude of and duration of a potential nuclear winter, the parameters of the exchange scenario, and policy recommendations, the most significant conclusion—that a nuclear exchange could fundamentally alter Earth's climate—had not been scientifically disproven or even sufficiently disputed. Despite the continued plausibility of nuclear winter and still substantially large US and Russian nuclear stockpiles, the interest and investments in nuclear winter research, for all intents and purposes, ceased for over a decade.

The Nuclear Winter Revival Era

The lull in nuclear winter research ended in 2007 with two publications on a study[81] modeling the climatic impacts of a regional nuclear conflict. These publications ignited a new era of nuclear winter research, currently ongoing, that primarily focuses on a possible nuclear exchange between India and Pakistan. The inaugural nuclear winter papers in the nuclear revival era[82] were part a joint assessment of the societal and climatic impacts of an India–Pakistan exchange. This assessment incorporated new climate models with full coupling of land and sea components. Researchers also took advantage of increased computing power, which allowed them to run these higher-fidelity models with longer simulation times. They found a global average cooling of 1.25 degrees Celsius persisting for years and a 10 percent reduction in global precipitation. Although they estimated substantially smaller climatic impacts than those predicted in the US–USSR exchange scenarios explored during the Cold War era, the 2007 study still concluded that "attacks totaling little more than one megaton of nuclear explosives could lead to global climate anomalies exceeding any changes experienced in recorded history."[83]

Robock, Toon, and collaborating scientists published a handful of additional studies on the same India–Pakistan exchange, including studies on

77 Some have claimed that nuclear winter helped persuade the US and Soviet governments to pursue significant arms reductions in the latter half of the 1980s. However, there is no definitive evidence that nuclear winter had a significant impact on these policies.

78 Turco et al., "Climate and Smoke"; and Ghan, "Chronic Climatic Effects."

79 Ghan, "Chronic Climatic Effects."

80 Ghan, "Chronic Climatic Effects."

81 Toon et al., "Atmospheric Effects and Societal Consequences"; and Robock et al., "Climatic Consequences."

82 Toon et al., "Atmospheric Effects and Societal Consequences"; and Robock et al., "Climatic Consequences."

83 Robock et al., "Climatic Consequences."

subsequent ozone depletion[84] and other societal impacts stemming from temperature and precipitation changes.[85] Several international studies were also conducted, one funded by the Task Force on Nuclear Disarmament and Non-Proliferation of the Swiss Federal Department of Foreign Affairs[86] and the other funded by Swedish Physicians against Nuclear Weapons.[87] In 2018 and 2020, respectively, two US Department of Energy national laboratories, Los Alamos National Laboratory[88] and Lawrence Livermore National Laboratory,[89] also published studies exploring the climatic impacts of the same India–Pakistan exchange.

The majority of the results from the India–Pakistan exchange studies during this era have been consistent with the earlier findings of Toon et al. and Robock et al.[90] However, as discussed in the Current Debate and Uncertainties section of this report, the Los Alamos National Laboratory study conducted by Reisner et al.[91] revealed inconsistent results.

The nuclear winter revival era also includes two studies of larger nuclear exchanges. Soon after the joint Toon and Robock study was published, the same group of scientists published a second study[92] exploring the climatic impact of larger (50- and 150-teragram) smoke injections into the atmosphere. Injections of this size are consistent with the Cold War–era studies based on a large US–USSR exchange. By using a modern global circulation model to explore these smoke injection scenarios, the authors found a global temperature decrease of seven to eight degrees Celsius and precipitation reduction of 45 percent, lasting for years.[93] In 2019, the same group repeated the study[94] with a different climate model and found the results to be consistent with their 2007 study.

The scientific papers published in this era have continued the trend of crossing over into the political realm by making policy recommendations based on their results. In their paper published in the *Journal of Geophysical Research*, Robock, Oman, and Stenchikov opined that "this continuing reduction of nuclear weapons by both parties is to be commended, but only nuclear disarmament will completely remove the possibility of a nuclear environmental catastrophe."[95] Robock and Toon went on to argue in a *Scientific American* article that "only abolition of nuclear weapons will prevent a potential nightmare. Immediate reduction of U.S. and Russian arsenals to the same levels as other nuclear powers (a few hundred) would maintain their deterrence, reduce the possibility of nuclear winter and encourage the rest of the world to continue to work toward the goal of elimination."[96] Additional examples of crossover into the political realm include the 2013 Stenke et al. paper, which concluded that "the best insurance against such a catastrophic development would be the delegitimization of nuclear weapons," [97] while Mills et al. wrote that "knowing the perils to human society and other forms of life on Earth of even small numbers of nuclear weapons, societies can better understand the urgent need to eliminate this danger worldwide."[98]

In contrast to the Cold War–era studies, the work in the nuclear winter revival era has not resulted

84 Mills et al., "Multidecadal Global Cooling."

85 Toon et al., "Rapidly Expanding Nuclear Arsenals."

86 Pausata et al., "Climate Effects."

87 Stenke et al., "Climate and Chemistry Effects."

88 Reisner et al., "Climate Impact."

89 Wagman et al., "Examining the Climate Effects."

90 Toon et al., "Atmospheric Effects and Societal Consequences"; and Robock et al., "Nuclear Winter Revisited."

91 Reisner et al., "Climate Impact."

92 Robock et al., "Nuclear Winter Revisited."

93 Robock et al., "Nuclear Winter Revisited."

94 Coupe et al., "Nuclear Winter Responses."

95 Robock et al., "Nuclear Winter Revisited."

96 Robock and Toon, "Local Nuclear War."

97 Stenke et al., "Climate and Chemistry Effects."

98 Mills et al., "Multidecadal Global Cooling."

in widespread government interest. Although some of the research from the nuclear winter revival era has been funded through government grants, there have been no congressional hearings or reports on recent nuclear winter studies, nor has the government directed the Department of Defense or Energy to conduct a comprehensive study on nuclear winter. The ongoing National Academies of Sciences, Engineering, and Medicine (NASEM) nuclear winter study, mandated by the 2021 National Defense Authorization Act,[99] confirms that some members of Congress are interested in revisiting nuclear winter research, but widespread and urgent interest appears lacking.

The trend in the nuclear winter research funding is one way of contrasting government interest between the two eras. In the 1980s, when nuclear winter research was at its peak, funding was primarily granted through government agencies to academic institutions or national laboratories. Funding came from sources such as the National Science Foundation,[100] the Department of Energy,[101] the Defense Nuclear Agency,[102] the General Accounting Office,[103] and the Australian government through the Department of Foreign Affairs.[104] By the start of the nuclear winter revival era, funding for studies focusing on an India–Pakistan nuclear exchange was through National Science Foundation grants, although the grants were not specifically directed at studying nuclear winter. Later studies were funded by various organizations, such as the Task Force on Nuclear Disarmament and Non-Proliferation of the Swiss Federal Department of Foreign Affairs,[105] the Swedish Physicians against Nuclear Weapons,[106] the Open Philanthropy Project,[107] and the National Nuclear Security Administration.[108] This shift in the funding trend suggests waning government interest in nuclear winter science after the Cold War era. In recent years, funding has mainly come from foundations and nongovernmental organizations concerned with nuclear disarmament and nonproliferation, highlighting the shift in interest from the government to the private sector.

In addition to the apparent reduction of US government interest, there has been no observable government interest from any of the nuclear powers, including the main actors in the studies, India and Pakistan.

Exploring the Apparent Loss of Government Interest

As discussed, by the early 1990s, initial widespread academic and political interest in nuclear winter largely died out. Government funding for nuclear winter studies diminished, as did the number of scientific and policy publications.

It is not clear why government interest waned, especially considering that the risk of nuclear winter was, and still is, highly uncertain and its occurrence would bring potentially devastating effects to the United States and much of the world. In this section, we formulate several hypotheses that could explain the decline of publicized government interest and develop rationales behind each. Through this analysis, we hope to better understand whether

99 William M. Thornberry National Defense Authorization Act for Fiscal Year 2021, Pub. L. No. 116-283 (2020).

100 Covey, Schneider, and Thompson, "Global Atmospheric Effects"; and Robock, "Snow and Ice Feedbacks."

101 Ghan, MacCracken, and Walton, "Climatic Response"; Ghan, "Chronic Climatic Effects"; MacCracken and Walton, "Effects of Interactive Transport and Scavenging"; and Malone et al., "Nuclear Winter."

102 Thompson, "Global Interactive Transport Simulations."

103 Bowsner, *Nuclear Winter*.

104 Pittock, Walsh, and Frederiksen, "General Circulation Model Simulation."

105 Pausata et al., "Climate Effects."

106 Stenke et al., "Climate and Chemistry Effects."

107 Toon et al., "Rapidly Expanding Nuclear Arsenals."

108 Reisner et al., "Climate Impact"; and Wagman et al., "Examining the Climate Effects."

this loss of interest was justified and whether interest should be rekindled.

Nuclear winter interest waned because of the end of the Cold War. This hypothesis is based on the belief that government interest in nuclear winter is highly dependent on the perceived likelihood of nuclear war. With the end of the Cold War, a large-scale nuclear exchange was increasingly viewed by political and military leaders, as well as the general public, as highly improbable. As a result of this perception, both the United States and Russia reduced the numbers and overall megatonnage of their nuclear arsenals. Thus, if nuclear war were to break out—however unexpectedly—the most extreme nuclear winter consequences would be averted. The overall effect of these changes was redirection of government grants from nuclear winter studies to what were perceived to be more pressing research concerns.

However, the perceived lower likelihood of nuclear war as the only or even primary reason for decreased government interest becomes increasingly dubious as the relief and euphoria over the unanticipated end of the Cold War and dissolution of the Soviet Union recedes into the distant past. In the past two decades, global attention has turned back to nuclear issues. Since the early 2000s, the nuclear stockpiles of India and Pakistan have quickly grown alongside continued tensions between the two nations. North Korea has developed nuclear weapons and has threatened their use against neighboring nations, South Korea and Japan, as well as against the United States. China is currently engaged in a large nuclear buildup that could enable it to become a nuclear peer of the United States by 2035.[109] Perhaps most important, the perceived risk of nuclear war between the United States and Russia or the United States and China has steadily increased with the resurgence of great power competition, as emphasized in the 2018 Nuclear Posture Review[110] and demonstrated by the Russian invasion of Ukraine and China's increasingly strident threats to invade Taiwan.

Yet, despite the perceived increase in the likelihood of nuclear war, it was not until very recently, through the 2021 National Defense Authorization Act mandating a NASEM study on the environmental effects of nuclear war, that the US government appeared to take renewed interest in nuclear winter. However, as discussed earlier, this study suggests concern of only several congresspersons, rather than of Congress as a whole or the executive branch. It remains to be seen what the results of the NASEM study will be or what effect the study will have.

There was no consensus on policy implications. One of the most significant unresolved disputes central to the nuclear winter debate was over which actions should be undertaken to reduce both the severity and likelihood of nuclear winter. There were numerous calls for total nuclear disarmament, or at least very large reductions in nuclear arsenals, to make the world safe from nuclear winter. However, without universal buy-in from all current and prospective nuclear states and ironclad mechanisms for ensuring compliance, this approach was readily dismissed as an impractical—even dangerous—solution.

Some argued that even without total disarmament or drastic reductions, the number and yields of nuclear weapons could still be reduced or targeting strategies adopted to prevent the more drastic nuclear winter predictions. Targeting strategies would call for deliberately avoiding targets, such as cities, whose bombing would cause the greatest amount of global cooling. However, some government officials were hesitant to support these ideas because they believed that US nuclear posture was

109 DOD, "Military and Security."

110 DOD, *Nuclear Posture Review*.

sufficient in reducing unwanted damage[111] or may have been uncertain how changes to targeting strategy would impact nuclear stability and deterrence.[112] Many accepted the belief that a large arsenal was critical to maintaining an effective deterrent, and many within the Department of Defense were loath to question that concept,[113] especially for an effect that was not scientifically "proven." Some even reasoned that nuclear winter strengthened deterrence since it made the consequences of nuclear war that much more dire.

The scientific credibility remained uncertain. Despite the significant scientific progress on nuclear winter research in the 1980s, pervasive and large uncertainties in the scientific results and large disagreements among studies persisted. Nuclear winter is a complex problem, an understanding of which requires multiple dynamically coupled scientific models and data from diverse scientific fields. Additionally, the climate models and the computing resources on which early studies relied were still in their infancy in the 1980s, forcing researchers to make broad assumptions to simplify the problem. Nuclear winter science also suffers from no direct evidence of the full phenomena, from nuclear detonation to climatic impacts, and it cannot be safely tested in a controlled setting.

While many scientific questions are arguably marked by larger uncertainties even after decades of research, nuclear winter science also suffers from being inconvenient. Because of the lack of consensus on policy implications, it has been more convenient for some to dismiss nuclear winter by questioning its scientific credibility, often citing the uncertainties and disagreements within the scientific community.

Nuclear winter was politicized from the onset. Nuclear winter was also dismissed by government officials as being politicized from the beginning. Some nuclear winter scientists were discredited because their predictions of severe nuclear winter effects seemed to align with their already established antinuclear agendas. This politicization provided some government officials a ready excuse to ignore the scientific conclusions. However, while some scientists engaged heavily in discussions on policy and politics, most did not, and the idea that the science was solely politically motivated has been largely discredited.

Where Do We Go from Here?

The context for addressing nuclear winter in national security policy has changed significantly since the end of the Cold War. A new cycle of nuclear winter studies emphasizes the risk from regional nuclear wars. In-progress nuclear winter studies funded by nongovernmental organizations are addressing the effects of physical climatic changes on human life, well-being, and the environment. Congress mandated an updated NASEM study of the atmospheric effects of nuclear war, including "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 debris on weather, agriculture, and long-term ecosystem viability."[114] In terms of the international security environment, new risks have emerged, and old risks have reemerged. The relatively recent rise of North Korea as a nuclear power presents new potential paths to nuclear war. As the exchange of threats between the United States and North Korea made clear, these new paths are not remote theoretical possibilities but are the bases of plausible scenarios. While North Korea's nuclear arsenal is

[111] DOD, "Potential Effects"; and *Nuclear Winter: Joint Hearing*.

[112] *Nuclear Winter: Joint Hearing*. Gertler, in *Some Policy Implications*, provides an overview of some of the policy implications of nuclear winter, including impacts to deterrence and extended deterrence.

[113] DOD, "Potential Effects," 174–175.

[114] Arms Control Association, "Congress Mandates Studies."

small, it is growing, and a nuclear war that starts with North Korea could escalate to involve multiple states with large arsenals. But most concerning of all is the increased nuclear risk associated with Russia's ambitions in eastern Europe. As of this writing, the possibility that Russia might use nuclear weapons in Ukraine remains a serious concern, as does the possibility of such use spiraling to a larger nuclear exchange. A final concern relates to China's rapid nuclear buildup that began in approximately 2020.

Under these circumstances, it is imperative to think through whether the government should take a renewed interest in understanding nuclear winter. One main question must be addressed before any decision is made: Is nuclear winter science plausibly sound? By *plausibly sound*, we mean there is credible scientific research that supports the concept, and although there may be uncertainties and variations in the extent of the consequences among studies, we cannot rule out impactful global effects. The answer to this question will be a major consideration in deciding among the following four main paths forward:

(1) Maintain the status quo

(2) Conduct more research

(3) Implement limited hedging against the effects of nuclear winter

(4) Make the world safe from nuclear winter

Maintain the Status Quo

One obvious path forward is simply to maintain the status quo. The United States would continue to develop and implement national security policy without openly considering the possibility and consequences of nuclear winter.

If nuclear winter science is assessed to be unsound, maintaining the status quo is a reasonable policy choice. Even if, on the other hand, the science is deemed plausibly sound, maintaining the status quo may still be a reasonable policy choice because hedging against nuclear winter could have detrimental effects on nuclear deterrence. In particular, drastic reductions in nuclear arsenals, as proposed by some nuclear winter scientists,[115] could undermine nuclear deterrence by reducing the direct and more certain immediate consequences of nuclear war and perhaps by encouraging conventional aggression that might escalate to nuclear war.

A related argument in favor of maintaining the status quo is the claim that nuclear winter should strengthen deterrence. To recap the argument, the goal of deterrence is to avert a nuclear attack. It accomplishes this goal by convincing would-be attackers that they would suffer "unacceptable" consequences of retaliation. If the nuclear winter science is assessed to be plausibly sound and nothing is done to reduce the consequences of nuclear winter, a nuclear exchange would be expected to produce long-term effects that are devastating globally, in addition to the already devastating immediate effects experienced by the warring countries. The only way to avoid these consequences would be to not attack. Thus, to the extent that the possibility of nuclear winter is a consideration in the minds of prospective attackers, maintaining the status quo should strengthen deterrence.

However, the argument that nuclear winter *should* strengthen deterrence does not mean that it actually *does*. The far-better-known horrific direct and immediate effects of nuclear war should be more than sufficient to deter any rational actor from assessing them as anything less than apocalyptic. Even more terrible consequences may add little to the deterrence calculus.

Finally, if the argument that nuclear winter strengthens deterrence is persuasive, it would be even more persuasive if the United States were to publicize the

115 Sagan, "Nuclear War and Climatic Catastrophe"; Sagan and Turco, "Nuclear Winter in the Post-Cold War Era"; Sagan et al., "Comment and Correspondence"; and Robock et al., "Nuclear Winter Revisited."

risks of nuclear winter—which it does not do. Why not? Because if the United States publicized such risks, it could appear to adversarial nuclear states that the United States is self-deterred from using nuclear weapons. Believing in the apocalyptic consequences of nuclear war, including—and perhaps especially—effects due to nuclear winter, could therefore undermine deterrence. These considerations are discussed in greater detail in our companion piece.[116]

The obvious downside to maintaining the status quo is that the potentially most severe consequence of a nuclear war may not be seriously considered. If nuclear war occurs and the nuclear winter scientists are correct, most of the world would suffer grievously and unnecessarily. Perhaps most important, nuclear powers have moral imperatives and legal obligations to consider the full spectrum of consequences of nuclear war. These obligations include not causing collateral damage that is grossly disproportionate to the military objective being pursued. It is hard to conceive of any military objective that could possibly justify billions of noncombatant fatalities.

Conduct More Research

An alternative path forward is to emphasize further research. A comprehensive, carefully conceived scientific research program, focused on resolving key uncertainties and gaining consensus among scientists, could provide the necessary basis for sound policy decisions. Complementing this scientific research would be a policy analysis program focused on developing and assessing alternative strategies for addressing whatever the scientific research reveals. In the absence of international support, such a two-pronged program would best be federally funded. Federal funding is important because it helps to ensure government buy-in, sufficient resources, and an overarching coordinating body. Last, the research should be easily traceable, open, and accessible to the public.

Ideally, this research program would involve a spectrum of current researchers in the field and encourage other scientists with relevant expertise to inject new ideas and analyses. It would extend analysis of consequences beyond effects on temperature and rainfall to consider the full spectrum of cascading effects on the physical environment, the biosphere, human well-being, and civilization. If sufficient government funding were provided for such a research program, scholars and scientists may be motivated to independently reengage on the topic of nuclear winter, reinvigorating academic research in the field.

One drawback to conducting more research is that, rather than forging a consensus of opinion, the research could be used as an excuse for inaction or delayed action. It could be argued that there have already been numerous peer-reviewed studies over the years, with the majority in general agreement on the severity of the climatic impacts of a nuclear exchange. If that is insufficient, at what point will the science be "believable" enough to spur serious consideration of policy changes? Waiting for the science to be completely certain before acting could result in perpetual inaction. If the more severe nuclear winter predictions prove to be true, this delay could be devastating.

Implement Limited Hedging against the Effects of Nuclear Winter

In conjunction with conducting more research, governments could implement limited hedging against the effects of nuclear winter. This would provide an opportunity to reduce the severity of nuclear winter while more research is being done. As an example of limited hedging, countries could continue to pursue arms control treaties to reduce arsenals. They could also reassess targeting strategies—including heights of burst, target selection, yields,

[116] Scouras, Ice, and Proper, *Nuclear Winter, Nuclear Strategy, Nuclear Risk*.

or even time of year—that could limit the more severe long-term consequences. They could push to pursue weapon designs that minimize nuclear winter effects, such as low-yield weapons, electromagnetic pulse weapons, and neutron bombs. Certainly some of these options are already being employed in targeting strategy. However, these options have not been implemented to minimize the effects of nuclear winter, and it is unclear exactly what impact they would have.

Equally important would be civil defense planning for postwar survival scenarios. This could include building up food stocks, seed banks, and water stocks and developing migration and other recovery plans, similar to measures that could ameliorate the effects of other possible disasters. Another mitigation possibility would be research on how the effects of nuclear winter might be reversed through geoengineering. Although many of these measures will be imperfect, they should not be neglected or rejected out of hand, as even small reductions in the severity of nuclear winter would be better than no reductions at all.

While some immediate actions could be taken to limit the effects of nuclear winter, their impacts on deterrence remain uncertain. If deterrence is adversely impacted, such actions could increase the probability of nuclear war. This should be fully understood before any strategy or policy changes are made, and more research is required to understand this potential effect.

It is also unclear whether any of these strategies would have significant impact on the severity of nuclear winter. Studies would need to be done to assess whether the policy changes would be worthwhile and how much they would reduce the global climatic and societal impacts. Finally, any efforts to limit the severity of a nuclear exchange would be more effective, and perhaps less dangerous, with buy-in from the other major nuclear powers.

Make the World Safe from Nuclear Winter

If nuclear winter science is deemed plausibly sound, there remains the question of what could be done beyond limited hedging options to significantly lessen the likelihood or ameliorate the consequences of nuclear winter. The only solution guaranteeing safety from nuclear winter is complete global nuclear disarmament, or at least dramatic reductions in current arsenals. As discussed, some nuclear winter scientists have argued for this,[117] but in our opinion, it is not a realistic goal for the foreseeable future. Therefore, other options must be considered.

One issue is the uncertainty around how much arsenals would need to be reduced to have a significant effect. It is reasonable to deduce that for nuclear armed states employing a countervalue targeting strategy, cities would be the last targets to be given up as arsenals are reduced, so the effects of lower numbers of nuclear weapons may not result in a commensurate decline in nuclear winter effects. And, unless yields are also constrained, lower numbers may drive nuclear states to higher yields, similarly frustrating the desired effect on nuclear winter. Another issue is that the effect of drastically reduced arsenals on the likelihood of a nuclear war is highly speculative. While these questions are amenable to further research, they may never be definitively answered.

It has been argued that in the face of drastic reductions in nuclear arsenals, deterrence would need to be maintained with other types of weapons.[118] This could include, but need not be limited to, cyber weapons, conventional military forces, and prompt global strike capabilities. Conventional military weapons, in particular, have been discussed and evaluated for decades as replacements for nuclear

117 Sagan, "Nuclear War and Climatic Catastrophe"; Sagan and Turco, "Nuclear Winter in the Post-Cold War Era"; Sagan et al., "Comment and Correspondence"; and Robock et al., "Nuclear Winter Revisited."

118 Baum, "Winter-Safe Deterrence."

weapons. We believe that some replacement of nuclear weapons by conventional weapons is feasible, but the possibilities are limited. Even if all current targets assigned to nuclear weapons could be held at risk by conventional weapons, such a wholesale replacement would severely undermine deterrence. We cannot conceive of a feasible alternative approach for maintaining deterrence and, indeed, do not believe one exists. Some of the more radical alternatives prompt immediate moral and ethical concerns, as discussed by Baum[119] and others.

In summary, there are enormous challenges associated with making the world safe from nuclear winter. To be effective, significant reduction of nuclear arsenals must be accompanied by universal buy-in from all nuclear states. Otherwise, it would undermine deterrence, and global climatic consequences after a nuclear exchange would still be a distinct possibility. There is the additional problem that alternative weapons are of dubious effectiveness in maintaining deterrence. For example, cyber weapons or conventional military forces may be detrimental to an adversary to a certain degree, but they are unlikely to prove as effective as nuclear weapons in preventing large-scale warfare between nuclear nations.

Our Recommendation

The Russian invasion of Ukraine has been accompanied by a disturbing level of implicit and explicit nuclear threats directed against the West, raising concerns about the possibility of escalation to nuclear war to levels that have not been experienced since the Cuban missile crisis. This does not bode well for a renewed interest in assessing and addressing nuclear winter. Instead, the nuclear policy focus in the aftermath of that war will probably be on shoring up deterrence and developing options for responding to nuclear first-use without provoking a spiral of escalation leading to unconstrained nuclear war. Nuclear winter is in danger of falling between the cracks once again.

Nevertheless, nuclear winter could become a more prominent consideration in nuclear policy. This might occur, for example, if the NASEM study currently underway results in a compelling assessment that the science is valid. On the darker side, if nuclear weapons are actually used in a conflict—even in a limited manner that does not result in any nuclear-winter-like effects—our focus on preventing nuclear war through deterrence might naturally become more balanced with consideration of mitigating the consequences of nuclear war. In that case, a resurgence of interest in nuclear winter might occur.

Based on these considerations and our judgment that nuclear winter science is not settled, we advocate for a comprehensive research program to resolve major uncertainties in fire ignition, smoke and soot production, and the lofting of these combustion products to the stratosphere. We further support research on the effects of climatic consequences of nuclear war on human life and well-being, civilization, and the environment. Additionally, we support further policy research focused on finding the right balance between preventing nuclear war and reducing its consequences, including those associated with nuclear winter. In particular, we support research and analysis into how measures proposed to lessen the effects of nuclear winter affect deterrence and stability.

In coming to these recommendations, we reject the other options discussed. Maintaining the status quo intentionally ignores what might well be the most severe consequence of nuclear war. It puts all our eggs in the “prevention” basket. But as nuclear proliferation grows, and in light of increasing tensions between the United States and both Russia and China, it seems sensible to recognize that nuclear war might actually occur. So it seems prudent to plan for that possibility and to try to reduce the most damaging consequences. We are not

119 Baum, “Winter-Safe Deterrence.”

opposed, in principle, to trying to hedge against nuclear winter consequences. But it seems that current suggestions focused on deep reductions in nuclear arsenals and tweaks to targeting doctrine would have marginal effects, would require cooperation with our nuclear adversaries, are impractical, or would take a long time to implement. We think it is wiser to first conduct needed research before embarking on such an effort. And, finally, the notion of a nuclear-winter-safe world, not unlike President Obama's vision of a nuclear-free world, simply will not be realized in our lifetimes. There is no substitute for threatening nuclear retaliation to deter nuclear attack and prevent nuclear intimidation. As Obama said in Prague shortly after his inauguration, "make no mistake: as long as these weapons exist, the United States will maintain a safe, secure and effective arsenal to deter any adversary, and guarantee that defense to our allies."[120]

Conclusions, Insights, and Recommendations

We have described nuclear winter science and the evolution of the nuclear winter debate, theorized why government interest in nuclear winter appears to have waned, and proposed several alternative paths forward. Our conclusions and recommendations are derived from this discussion, but we also include additional insights gleaned over the course of several years of thinking and debating about the nuclear winter saga.

(1) Nuclear winter is potentially among the most severe consequences of nuclear war, but the science remains fraught with uncertainties.

Prior to the TTAPS paper, it was well understood that nuclear war would be devastating to combatant states, but we were unaware of the potential for nuclear winter and the additional risk to billions of people throughout the world, most of them unintended victims of the warring states. So, we owe a great debt to Crutzen and Birks and the TTAPS scientists for first sounding the alarm, even if the initial models were crude and their results uncertain.

Since the original TTAPS paper, the basic phenomenological understanding of all the steps in the process—target selection, burning and lofting, stratospheric dispersal, attenuation of sunlight, and ultimately recovery—has continued to improve. Nevertheless, four decades later, the extent to which a "modest" nuclear exchange between regional nuclear powers, or even a large nuclear exchange between the major nuclear states, could impact the global climate is still highly contested. Given the potential consequences at stake, we are struck by how little nuclear winter research there has been, how few scientists have been involved in the research, and how limited the collaboration has been between the few groups conducting research.

It has been difficult for the three authors of this paper—PhD physicists all—to sort out the state of nuclear winter science. As we have noted, nuclear winter is a complex phenomenon involving multiple intertwined and dynamic processes, each requiring a highly specialized area of expertise. Complex models and simulations are used to study the phenomenon, and the resulting scientific papers are necessarily incomplete in their descriptions of models and definitions of model inputs. Sometimes key assumptions about critical parameters such as fuel loading and lofting altitudes are buried in previous studies. In short, technical papers on nuclear winter are not easily evaluated, even by scientists, and comparisons across papers are even more challenging. We are concerned that similar difficulties are encountered in the peer review process for publishing these papers in journals—specifically, that the only competent peer reviewers might also be selected from the small pool of nuclear winter scientists, raising questions about the independence and lack of bias in the process.

120 White House, "Remarks by President Barack Obama."

In any event, it is clear that the general public is unable to critically assess most scientific papers. Thus, they must rely on trusted interpreters. Unfortunately, biases can creep in here as well. It is no exaggeration to observe that the prospect of nuclear winter has become a weapon to wield by those who favor reducing nuclear arsenals. Uncertainty, which breeds skepticism in nuclear winter science, has similarly become a weapon for those who favor a strong nuclear deterrent. What has become eminently clear to us is that scientists' and policy analysts' positions on nuclear winter are highly correlated with their positions on nuclear weapons and deterrence more generally.

(2) Initial widespread interest waned because of a combination of factors, principally the end of the Cold War but also the impracticality of policy solutions, the problematic mixture of science and politics, and difficulties in resolving scientific uncertainties.

The dire and surprising predictions in the TTAPS paper initiated a flurry of research in the last decade of the Cold War. The end of the Cold War was accompanied by a greatly diminished perception of the threat of nuclear war and a dramatic decline in US and Russian arsenals. A decade later, the terrorist attacks of September 11, 2001, further diminished attention devoted to nuclear issues (except for the threat of nuclear terrorism). Subsequently, the wars in Afghanistan and Iraq dominated military thinking and spending. Only fairly recently has the threat from Russia, as well as the nuclear threat from China, reemerged as a primary concern in defense strategy.[121]

Nuclear winter research might have had a greater impact on policy if the only certain solution had not been eliminating most nuclear weapons from planet Earth. Beyond the United States drastically reducing its arsenal, eradicating most nuclear weapons would have also required Russia and all other nuclear states to do so as well. However, as President Obama's Global Zero initiative demonstrated, the challenges of eliminating all nuclear weapons appear to be insurmountable in the foreseeable future.

On the other hand, we are surprised by the evident lack of concern regarding nuclear winter science within both the Department of Defense and government more broadly. While the science is still uncertain and consensus on the magnitude of the climatic impact has not been reached, the theory that a nuclear exchange would have consequences on the global climate has not been scientifically disproven or even credibly challenged. Because of nuclear winter's potential implications on nuclear deterrence and its possible failure, it is critical that the US government and the governments of other nuclear nations seriously consider the possibility that a nuclear exchange could adversely impact the global climate.

(3) With increased proliferation and increasing concern about nuclear threats from Russia and China, the science and policy implications of nuclear winter need to be addressed anew.

Two factors are necessary to launch a successful nuclear winter research endeavor and avoid policy inaction. First, high-level government interest needs to be rekindled. Without top cover, low- and mid-level echelons in the Department of Defense and elsewhere in government are not likely to be able to generate sustained interest in nuclear winter research. By contrast, high-level government interest will stimulate research funds for both scientific and policy studies, which in turn, will likely prompt similar endeavors in academia. We are encouraged that Congress, through the 2021 National Defense Authorization Act, has directed the administrator for nuclear security, in consultation with the secretary of defense and the director of national intelligence, to commission a NASEM study on the environmental effects of nuclear war.

121 For a more detailed discussion of evolving perspectives on nuclear threat, refer to Scouras et al., *On Assessing the Risk of Nuclear War*, chapters 1 and 9.

A complementary study, perhaps best conducted by a panel of experts outside of government, could identify and evaluate—based on our current understanding of the climatic impacts of nuclear war—policy initiatives designed to minimize the risk of nuclear winter. These studies could help kick-start the high-level government interest needed for a sustained initiative.

Second, the government needs to resume funding independent research on nuclear winter. We hope that the NASEM study on the atmospheric effects of nuclear war motivates a government-funded research program that would reduce uncertainties and move the scientific community toward consensus. Research planning and oversight are needed to ensure that future research is devoid of political bias to the extent feasible. Further, competitive analyses should be an integral part of any new research program and could help expose biases. A comprehensive research effort would also bring in a wider diversity of researchers to focus on the key variables of the nuclear winter phenomenon, such as nuclear war scenario development and fuel loading, as well as smoke lofting. These variables are key to understanding the climatic impacts of a nuclear war but are often outside of the expertise of the scientists conducting this research. Finally, the nuclear states, and perhaps also nonnuclear states, should participate in research.

A Final Thought

The troublesome nuclear winter saga is in many ways a common tale of all-too-human fallibilities. The unfortunate commingling of science and politics, originating in Sagan's initial *Parade* article, which publicized the term *nuclear winter*, awakened the general public to this dire consequence of nuclear war; implicitly criticized the defense community for failure to be aware of this consequence (and for other surprises); suggested the need for infeasible reductions in nuclear arsenals; and set the stage for contentious debate on both the underlying science and policy inaction. It seems to us that too many proponents—scientists and policy analysts alike—on both sides of the debate were and remain biased. More than a few scientists and policy analysts blatantly wielded uncertain science as a weapon to support previously held beliefs on nuclear weapons. The debate has thus changed few minds and has resulted in essentially no policy impact. Scientists should be more disciplined when delving into policy. Policymakers should not dwell on uncertainties as an excuse for inaction. Responsible government entities should not disregard nuclear winter. The science should not be ignored because it is inconvenient or because uncertainties exist. We need to do better, and we can do better. Our future depends on it.

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Appendix A Literature Reviewed

The scientific articles we chose for review for this study are comprehensive studies that model a full exchange scenario from black carbon injection through to climatic impacts. Although numerous, parameter-specific studies (e.g., those on lofting or participle composition) were not included in the literature review. The policy papers range from short commentaries to transcripts of congressional hearings dedicated to nuclear winter. We did not capture literature associated with public interpretation of nuclear winter, such as newspaper articles, leaving the response of the general public open for future analysis. Both the scientific studies and policy papers included are those known to the authors at the time of the research and may not constitute a full list of papers. Listed below are the citations.

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- Statement of Dr. George F. Carrier (Harvard University, Cambridge, MA; and chair of the Committee on Atmospheric Effects of Nuclear Explosions, National Academy of Sciences)
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