

Ronald Reagan Presidential Library Digital Library Collections

This is a PDF of a folder from our textual collections.

Collection: Keyworth, George: Files
Folder Title: Nuclear Winter (2)
Box: RAC Box 11

To see more digitized collections visit:

<https://www.reaganlibrary.gov/archives/digitized-textual-material>

To see all Ronald Reagan Presidential Library inventories visit:

<https://www.reaganlibrary.gov/archives/white-house-inventories>

Contact a reference archivist at: **reagan.library@nara.gov**

Citation Guidelines: <https://reaganlibrary.gov/archives/research-support/citation-guide>

National Archives Catalogue: <https://catalog.archives.gov/>

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20506

February 28, 1985

Dave,

This is DoD's response to legislative requirements on nuclear winter. It's mostly mush.

Jay Keyworth

THE WHITE HOUSE
WASHINGTON

Date Mar. 4, 1985

FOR: Jay Keyworth

FROM: **DAVID B. WALLER**

ACTION

- ☐ For your information
- ☐ For your review and comment
- ☐ As we discussed
- ☐ For your files
- ☐ Please see me
- ☐ Return to me after your review

COMMENT

Thanks for the information on the subject
of the Report assessing climactic effects
of nuclear war.

File "Nuclear Winter"

Prepared by the National Climate Program Office, NOAA

February 5, 1985

REPORT TO THE OFFICE OF SCIENCE
TECHNOLOGY AND POLICY

INTERAGENCY RESEARCH REPORT
FOR ASSESSING CLIMATIC
EFFECTS OF NUCLEAR WAR

Prepared by the National Climate Program Office, NOAA

February 5, 1985

PREFACE

Presidential Science Advisor Dr. George Keyworth II requested that the National Climate Program Office, NOAA, develop an interagency research plan which addresses the climatic effects of nuclear war. The research plan was prepared by a panel of federal and university scientists convened by the National Climate Program Office (Committee B). The plan identifies priorities for a coordinated interagency program designed to reduce the uncertainties in the various parameters of climatic conditions after a nuclear exchange. The plan was approved by an interagency review committee (Committee A) for submission to the Office of Science and Technology Policy (OSTP). Membership of committees A and B are given in Appendix A. Copies of this plan are available from the Executive Office of the President, Office of Science and Technology Policy, Washington, D.C. 20506.

OUTLINE

Executive Summary.....	p. 3
1. Overall Strategy.....	p. 9
2. Brief Review of Recent Studies.....	p. 14
3. Reducing Uncertainties in the Generation and Evolution of Source Material.....	p. 20
A. Smoke Emission.....	p. 20
B. Optical and Other Properties.....	p. 22
C. Plume and Cloud Dynamics.....	p. 24
D. Cloud Interactions and Removal Processes...	p. 27
E. Atmospheric Chemistry.....	p. 30
4. Laboratory and Field Experiments, and Analyses.....	p. 34
A. Nonurban.....	p. 36
B. Urban.....	p. 37
C. Fire Rapid-Response.....	p. 39
D. Other Experiments and Related Studies.....	p. 40
5. Improvements in Modeling and Atmospheric Processes.....	p. 42
A. Radiation.....	p. 42
B. Plume and Cloud Interaction Modeling.....	p. 44
C. Mesoscale and Global Effects	p. 46
6. Agency Responsibilities.....	p. 55
References.....	p. 61

Appendix A - National Research Plan Committees

Appendix B - Ranges of Uncertainties in "Nuclear Winter" Calculations
(prepared by Michael MacCracken, LLL)

EXECUTIVE SUMMARY

1. The purpose of this document is to present a research plan that addresses the need for a rapid improvement in understanding and for reducing important uncertainties in the "nuclear winter" hypothesis. The plan lays out the basic strategy for a coordinated interagency program.

2. Recent modeling studies of the likelihood of extensive fires following multiple nuclear explosions have suggested that a prolonged period of subfreezing surface land temperatures might occur following a limited or full scale nuclear war. The basic hypothesis of a "nuclear winter" is that the smoke and dust produced during nuclear fires and explosions, once it is lofted high in the atmosphere, would block much of the sunlight reaching the earth's surface. Of these two types of particles, the smoke is thought to have a greater effect on climate because it absorbs sunlight.

3. However, these studies, like any modeling exercise, are strongly dependent on source inputs, model assumptions, and representative target data bases. Because of the uncertainties in source inputs and the present level of sophistication in models, the hypothesis of a nuclear winter cannot be accepted or rejected at this time.

4. Source inputs for the smoke component depend on the character of fires (size, intensity, distribution, combustibles), which determine the amount of particulate matter produced and its optical properties, and local meteorological condition. Source inputs for the dust component are thought to

be better understood and depend on the excavation of surface material by ground bursts.

5. Air heated by an extended fire rises convectively carrying with it smoke and other entrained material such as ash and dust. Just where this particulate material is carried depends on the area of the fire and its intensity, the turbulence in the flow and the entrainment of unheated air, the conditions of temperature and humidity in the ambient atmosphere, and the local wind fields. In general, the larger and more intense the fire, the higher the plume (and smoke) will rise. The higher in the troposphere the smoke is injected, the more persistent it will be and the more effect it is expected to have on surface temperatures. Very intense fires, firestorms, may even inject material into the stratosphere.

6. Microphysical and plume-cloud interactions on scales up to 100 km strongly determine the height of smoke plume injection and early rainout. Mesoscale processes on scales of 10 to 1000 km strongly determine mixing and smoke removal. There are large uncertainties in understanding atmospheric processes on the micro, plume-cloud, and mesoscales.

7. Events in the first hours and days following a nuclear exchange are crucial in determining the composition and amount of source input, the height of dust and smoke injection into the atmosphere, and the initial degree of scavenging and rainout of smoke.

8. Climate models provide the only means to simulate global-scale atmospheric effects of nuclear war. While these models are sophisticated and

are capable of successfully simulating many aspects of the observed weather and climate, including the seasonal cycle, there are many aspects of these models that have not been designed to adequately represent the climatic effects of very large smoke injections. The interactive effect of large amounts of smoke must be considered in existing climate models for results to be more realistic.

9. The determination of a representative target data base which includes expected yield, location and types of targets, sequencing, types of explosions, etc. will greatly affect the result of model studies. A plausible target data base is needed for estimating the resultant climatic effect.

10. The priorities of the research program are to address the major uncertainties in source inputs, improve modeling of atmospheric effects of nuclear war, and provide a plausible set of climatic conditions for assessing consequences. Not all uncertainties of source inputs and climatic effect can be reduced, but it is possible to considerably improve knowledge of the climatic consequences of nuclear war and thus put decision-making at all levels on a firmer scientific basis.

11. Various research strategies are proposed which include: Theoretical studies and laboratory experiments, field experiments, diagnostic studies, modeling and assessment studies.

12. Theoretical studies of the detailed chemistry and physics of the combustion process with the fluid mechanics and energy transfer factors under which they occur can help in the design of relevant laboratory experiments and

also extend their results.

13. Laboratory experiments will help in determining the amount of smoke formed in initial fires, the aerosol yield from mixed fuels, the chemical composition of the smoke, particle sizes and optical properties of smoke, coagulation potential of mixed fuel sources, and dynamics of mixed fuel source-smoke interactions.

14. Field experiments involving managed fires, primarily of vegetation, are planned for routine and special burns to study the initial height reached by the smoke and its early removal and spreading under different environmental conditions.

15. Satellites can rapidly identify large fires and provide data which will be useful in studying the spread of smoke plumes from extensive forest fires, their heights of injection, and optical priorities. A limited rapid fire-response program can be planned to sample fuel loading, atmospheric conditions, particulate and chemical effluent, and to assess the atmospheric interactions that follow from fires of opportunity.

16. The degree to which the results of laboratory and field fire experiments can be extrapolated to large-scale urban and vegetative fires is unknown. Proposed scaling experiments are crucial first steps in addressing this uncertainty.

17. Diagnostic studies of both historical and contemporary data may yield insight into the effects of dust and smoke based on analogues of previous

large fires. Tropical burning and desert dust storms represent the best large-scale analogues of the nuclear winter.

18. Modeling studies involving present cloud, mesoscale, and global circulation models will be made in order to improve our knowledge of the lifetime of the particles in the atmosphere, the rapidity and scale of their dispersal, and the resultant changes in climate. Emphasis will be placed on interactive processes between the particles and other elements of the climate system.

19. Although much of the debris from a nuclear war will be injected into the troposphere, substantial dust and possibly soot may be ejected into the stratosphere. Global models devoted to stratospheric dynamics will be needed to properly evaluate the effect of stratospheric debris.

20. The minimum results of this plan should be (1) improved estimates of fuel loading in urban and nonurban environments; (2) reduction in the range of estimates of smoke emissions and interactions in the atmosphere; (3) determination of physical and optical properties of smoke for fires of different sizes, intensities, and composition; (4) direct measurements of radiative effects for a variety of smoke and dust conditions; (5) improved simulation of climate effects using models which include interactive smoke spreading and scavenging, diurnal and seasonal cycles, and improved parameterizations; (6) narrower ranges of possible climate impacts; (7) determination of yield-atmospheric loading relationships for policy consideration, such as threshold levels for significant climate changes; and (8) preliminary assessment of environmental issues other than smoke and dust.

21. Major advances are needed in the overall state of global modeling before the atmospheric processes leading to a "nuclear winter" can be reasonably assessed. These include the effects of the atmosphere on the "cloud" in the very early stages as well as in the longer term, the effect of the "cloud" on the atmosphere, the interaction between the different scales of activities, and the response of the atmosphere to abnormal conditions never before experienced. This plan proposes to make an initial effort to address these areas for improving global modeling.

22. Evaluating the first order climatic consequences of nuclear war is extremely complex and requires the expertise of many disciplines. A carefully planned coordinated research effort is required to develop a more realistic picture of possible environmental consequences. The "nuclear winter" problem, however, is embedded in more general problems of understanding fire phenomenology, atmospheric chemistry and physics, mesoscale and global circulation, and cloud dynamics.

1. OVERALL STRATEGY

Problem

The hypothesis underlying a "nuclear winter" is that dust raised by surface bursts and smoke produced by thousands of fires initiated by a moderate or large-scale nuclear exchange would spread over much of the globe and cause the average surface land temperatures to drop sharply (even to below freezing) for up to several months. Preliminary scientific estimates of the effects are, however, based on many assumptions and uncertainties. These include nuclear war scenarios, estimates of how much smoke is produced during fires, how much dust is raised by explosions, how high smoke and dust are injected into the atmosphere, how much of the material is retained in the atmosphere and for how long, how the smoke and dust interact with and are distributed in the atmosphere, and how this material alters the radiation balance and general circulation of the atmosphere. Estimates of the plausible ranges of uncertainties for these parameters are given in Appendix B.

The objective of this interagency plan is to present a research program that addresses the need for a rapid improvement in understanding and reducing important uncertainties in the "nuclear winter" hypothesis. Time and resources do not permit this plan to be a comprehensive review or assessment; rather, the plan lays out a basic strategy for a coordinated interagency program. The program includes many parts which together form an "ideal" research agenda. It is a carefully crafted program that builds and enhances existing knowledge. It provides for exploratory review of issues other than smoke and dust that exist in published reports to determine whether any of these require a major assessment. These studies are crucial for anticipating

other nuclear effects issues.

Proposed Program

While new observational, theoretical, and modeling studies in atmospheric chemistry, cloud physics, and mesoscale and global circulation will contribute to the goals of the plan, major reductions in present uncertainties require both better data on source inputs and better representation of atmospheric effects. Inventories of possible fuel sources in urban and nonurban areas are now being collected and provide a statistical basis for estimating potential smoke emissions. Laboratory and field studies are required, however, to quantitatively describe the physical characteristics of smoke emissions and their potential longevity in the atmosphere. While the problem of evaluating the climatic consequences of nuclear war is somewhat dependent on the types and locations of nuclear explosions, we are still greatly hampered by an insufficient modeling capability needed to disperse and distribute smoke and to extrapolate to the types of fires which might be produced.

It is the recommendation of the drafting committee (Committee B) for the research plan that highest priority be given to (1) implementation of a suite of carefully planned laboratory and field fire experiments and (2) modeling studies to better describe the properties of potential source inputs to the atmosphere and their subsequent radiative, cloud, and chemical interactions.

Laboratory experiments on urban and vegetative material can provide valuable information on smoke characteristics, coagulation, and optical properties. Such experiments must be jointly planned by experimenters and theoreticians. A number of large-scale prescribed fires are purposely set each year by forest managers, and these will provide opportunities for field studies. In addition, a fire rapid-response program can be organized to study

anticipated fires of opportunity.

Besides experimental studies of individual fires, there are regional-scale natural phenomena which have some characteristics of the aerosols input of a "nuclear winter." The best-known analogues are the burning of tropical forests (in slash-and-burn farming) and dust storms. By measuring the amount of soot which is naturally injected in the atmosphere and the steady state loading of the atmosphere in the tropics, insight may be gained into the processes that remove soot from the atmosphere. Saharan dust storms are optically dense enough to cause surface temperatures to drop many degrees for short periods. Studies of these events may better reveal how the thermal structure of the atmosphere changes when aerosol clouds are present and how aerosols are transported and removed from the atmosphere. These natural analogues provide our only experimental tests of the large-scale dynamical response of the atmosphere to heavy loading.

Global models provide the only means of simulating global scale effects of nuclear war. These models are crucial for decision making at all levels. Thus, concurrent with the above laboratory and field efforts, an accelerated and well-organized national effort is needed to improve atmospheric modeling from small to large scales, including the important interactions among various scales. A series of model improvements in physical representations and parameterizations can now be implemented in existing atmospheric models to provide a more realistic assessment of climatic consequences. New observational data derived from the fire experiments will be useful in validating the smaller scale models and in providing input to all of the modeling experiments.

These combined efforts on theory, experiment, observation, and modeling, linked together, can provide maximum scientific leverage to reduce major

uncertainties in understanding the atmospheric consequences of nuclear war.

Evaluating the first-order climatic consequences of nuclear war is extremely complex and requires the expertise of many disciplines. There are no quick experiments or model simulations that will adequately estimate the outcome. Rather, a carefully planned coordinated research effort is required to develop a more realistic picture of environmental consequences. Not all uncertainties can be eliminated, but a better knowledge of the range of possibilities can be obtained.

Program Implementation

While DOD and DOE have research efforts underway at present, any interagency plan should draw upon contributions from other federal agencies and university scientists who have expertise, equipment, and experience applicable to the problem of the climatic consequences of nuclear war. This effort will coordinate national resources for theoretical and field experiments and modeling studies considering the availability of total funds, thus maximizing the entire research and development effort.

Summary

It is possible to improve considerably knowledge of the climatic consequences of nuclear war. Expertise, equipment, and scientific commitment are available to accomplish this. The problem, however, requires strong interagency coordination to ensure a balanced and cost-effective program. The plan proposes an effort focused on theoretical studies, laboratory and field experiments, and modeling studies. The experiments are aimed at reducing the largest uncertainties in the "nuclear winter" hypothesis. Concurrent development of representative target data bases will be used for input into

the theoretical modeling studies. The results of these studies should be unclassified and available to the scientific community through standard scientific journals and technical reports.

2. BRIEF REVIEW OF RECENT STUDIES

The concept of a "nuclear winter" is based on the proposition that large-scale fires and excavated debris produced by many nuclear explosions would create a hemispheric to global blanket of smoke and dust sufficient to greatly reduce the amount of sunlight reaching the earth's surface. A prolonged period of sharply reduced land surface temperatures would follow for much of the northern hemisphere, and perhaps the world. The relevance of dust to this hypothesis is based on studies related to dust storms on Mars and the extinction of the dinosaur, some 60 million years ago. L. Alvarez et al. (1980) postulated that an asteroid hitting the earth put so much dust into the atmosphere that sunlight and photosynthesis were significantly reduced long enough to lead to extinctions for large species. The Alvarez hypothesis stimulated researchers and others to calculate the possible climatic effect of such a massive dust cloud, and the National Academy of Sciences to reassess the effects of dust on climate.

Crutzen and Birks (1982) were the first to attempt to quantify the possible input of smoke into the atmosphere from burning forests following a nuclear war. They concluded that for periods of several weeks or longer, such fires would produce sufficient smoke to reduce incoming solar radiation over wide areas of the earth's surface to below that required for photosynthesis. They conclude that:

"As a result of a nuclear war, vast areas of forests will go up in smoke - corresponding at least to the combined land mass of Denmark, Norway and Sweden. In addition to the tremendous fires that will burn for weeks in cities and industrial centers, fires will also rage across croplands and it is likely that at least 1.5 billion tons of stored fossil fuels (mostly oil and gas) will be destroyed. The fires will

produce a thick smoke layer that will drastically reduce the amount of sunlight reaching the earth's surface. This darkness would persist for many weeks, rendering any agricultural activity in the Northern Hemisphere virtually impossible if the war takes place during the growing season."

A subsequent study by Crutzen, Galbally, and Bruehl (1984) using a simple rainout procedure, aerosol physics, and radiative equilibrium models reaffirms their basic conclusion. But their analysis is "based on very few and uncertain data from simple laboratory tests, the results of which were extrapolated to mass fires. The numerical results of this study should, therefore, not be taken too exactly."

The first major studies of the climate and biological consequences of nuclear war from both dust and smoke were published by Turco, Toon, Ackerman, Pollack and Sagan (known as TTAPS) and Paul Ehrlich et al. in Science in 1983. The TTAPS report coined the term "nuclear winter" and said that

"For many simulated exchanges of several thousand megatons, in which dust and smoke are generated and encircle the earth within 1 to 2 weeks, average light levels can be reduced to a few percent of ambient and land temperatures can reach -15° to -25°C . The yield threshold for major optical and climatic consequences may be very low: only about 100 megatons detonated over major urban centers can create average hemispheric smoke optical depths greater than 2 for weeks and, even in summer, subfreezing land temperatures for months. In a 5000-megaton war, at northern mid-latitude sites remote from targets, radioactive fallout on time scales of days to weeks can lead to chronic mean doses of up to 50 rads from external whole-body gamma-ray exposure, with a likely equal or greater internal dose from biologically active radionuclides. Large horizontal and vertical temperature gradients caused by absorption of sunlight in smoke and dust clouds may greatly accelerate transport of particles and radioactivity from the northern hemisphere to the southern hemisphere. When combined with the prompt destruction from nuclear blast fires, and fallout and the later enhancement of solar ultraviolet radiation due to ozone depletion, long-term exposure to cold, dark, and radioactivity could pose a serious threat to human survivors and to other species."

Paul Ehrlich and 19 co-authors analyzed the consequences of many months

of subfreezing temperatures, low light levels, and high doses of ionizing and ultraviolet radiation on global biological systems. They conclude that survivors of a nuclear war would face starvation as well as

"freezing conditions in the dark and exposure to near-lethal doses of radiation. If as now seems possible the southern hemisphere were affected also, global disruption of the biosphere could ensue. In any event, there would be severe consequences, even in the areas not affected directly, because of the interdependence of the world economy. In either case the extinction of a large fraction of the earth's animals, plants, and microorganisms seems possible. The population size of Homo sapiens conceivably could be reduced to prehistoric levels or below, and extinction of the human species itself cannot be excluded."

"Nuclear winter" is a new dimension of the possible consequences of nuclear explosions. A 1975 report of the U.S. National Academy of Sciences did not consider the climatic effects of nuclear war significant. The main concern of the report was potential damage to ozone in the stratosphere. From comparison with volcanic eruptions, the report concluded that "stratospheric dust injection from a 10,000 megaton nuclear exchange would be comparable with that from a large volcanic explosion such as that of Krakatoa in 1883 and therefore might have similar climatic impact. At most, a 0.5°C deviation from the average lasting for a few years might be expected." No input from large-scale fires was recognized in this report. An earlier Academy report did identify the possibility of lingering fires in a post-nuclear world, although with uncertain ecological consequences (NAS, 1968).

The climatic consequences of nuclear explosions have been analyzed by two major dynamical modeling groups and others in the United States and by the Computing Center of the USSR Academy of Sciences. Results from the Lawrence Livermore National Laboratory (LLN) two-dimensional atmospheric circulation model were presented at the Third International Conference on Nuclear War in

Erice, Sicily (1983). MacCracken, using the LLL model with a 10° latitude resolution and 9 layers in the vertical atmosphere, extending up to 35 km, showed that the cooling averaged over all northern hemisphere land surfaces will be $10\text{--}15^{\circ}\text{C}$ within a few days of the smoke injection.

Analysis by Covey, Schneider and Thompson (1984) with the NCAR community climate model, a three-dimensional general circulation model using 4.5° latitude and 7.5° longitude resolution with 9 vertical layers, shows substantial surface cooling for tropospheric aerosols of absorption optical depth 3 injected in the northern hemisphere midlatitudes and maintained for 3 weeks. They conclude that:

"Mid-latitude surface temperatures in continental interiors can drop well below freezing in a matter of days regardless of season. Our results, although based on several assumptions, suggest that circulation changes caused by aerosol-induced atmospheric radiative heating could spread the aerosols well beyond the altitude and latitude zones in which the smoke was initially generated."

The model employed at the Computing Center of the USSR Academy of Sciences is an extension of the Mintz-Arakawa model of the Global Circulation (Gates et al, 1971) with horizontal resolution of 12° latitude by 15° longitude and two vertical layers representing the troposphere from the surface to about 12 kilometers. The aerosol distribution in the Soviet model is based on the TTAPS 10,000 megaton war scenario with smoke of average optical depth 3.5 distributed between 12° and 90°N latitude. Initial results show a temperature decline of as much as 25°C over large continental areas beneath the smoke cloud (Aleksandrov and Stenchikov, 1983).

A comparison of modeling results between the NCAR general circulation model and the climate model at the Computing Center of the USSR Academy of Sciences has been prepared by S.L. Thompson, et al. (1984). Both models

produce subfreezing land surface temperatures under a dense northern hemisphere smoke cloud, particularly in continental interiors.

Robock (1984) has recently suggested, on the basis of a seasonal energy balance climate model, that the climatic effects of a nuclear war might persist for several years because of feedbacks in the climate system due to snow/albedo and sea-ice/thermal inertia changes. These feedbacks become important in the years following a nuclear exchange when the initial dust and smoke perturbation has been reduced.

Calculations of climatic effects by different models have given similar results when the same essential assumptions are made. These include uniform injection of 200 to 300 teragrams of black smoke into the troposphere of the northern hemisphere. However, key assumptions of amount, injection altitude, optical properties of smoke, and early removal or scavenging processes have not been independently determined. None of the calculations published to date have been interactive in the sense of calculating the spread of smoke, its effects on the weather, and the subsequent effects on the scavenging of the injected materials.

S.F. Singer, S.L. Thompson, S. Schneider, and Covey exchanged views on the possible extent of a nuclear winter in Nature (1984). They identified many of the uncertainties associated with estimating source material from nuclear explosions and fires and the limitations of current modeling. Singer is not alone in expressing skepticism about some of the seemingly extreme "nuclear winter" effects (Teller, 1984).

Policy implications of "nuclear winter" effects have been argued by Sagan (1984), and more general nontechnical reviews of a "nuclear winter" have been published by P. Ehrlich (1984) and A. Ehrlich (1984). A history of such studies leading up to 1984 is given by Schneider and Londer (1984). An

extensive discussion of both the atmospheric and the biological consequences of nuclear war, with emphasis on "nuclear winter," is given in the recent book by Ehrlich et al., 1984. A renewed assessment of climatic effects of nuclear war has been completed by the NAS (1984). The Academy concludes that despite large uncertainties in source inputs and modeling, there is reason to expect widespread climatic affects due to extensive fires caused by nuclear exchange.

Many of the statements and conclusions cited above are being debated in the scientific community. Many uncertainties exist in the underlying assumptions and in available data bases. The interagency research plan presented here is designed to address these basic scientific issues and uncertainties.

3. REDUCING UNCERTAINTIES IN GENERATION AND EVOLUTION OF SOURCE MATERIAL

The major uncertainties in evaluating the climatic effects of a nuclear exchange relate to estimates of the amounts, altitudes of injection, and properties of dust and the smoke generated in large-scale urban and vegetative fires, and their subsequent interaction with the atmosphere. Atmospheric processes and factors involved are shown in figure 1 and summarized in table 1. The discussion that follows reviews these uncertainties and identifies measurements required to resolve them. The main conclusion is that many of these crucial questions can be treated in both laboratory and field experiments.

Smoke Emission

Many factors determine the amount of material burned in a fire. These include fuel type and distribution, the distribution of ignition points, the fire spread, and the fraction of available fuel which actually burns. The fraction of burned material which is converted to particulate matter, in turn, depends on these and other factors, including the oxygen environment in which the principal combustion takes place, the residence time of soot particles within the flame (burnout), and the thermal environment in which soot formation takes place. Substances that have significant innate oxygen in their composition (such as the cellulose in wood, phytomass, and some fabrics) burn somewhat cleaner, all other things being equal, than substances which are less well oxygenated. Some substances not well oxygenated can also burn rather efficiently and produce little smoke by virtue of the volatile and combustible nature of their pyrolytic emissions. By contrast, some materials (some plastics and wood lignins) have copious soot emissions when they burn.

Figure 1: Schematic representation of major components of forest fires relevant to "nuclear winter" studies.

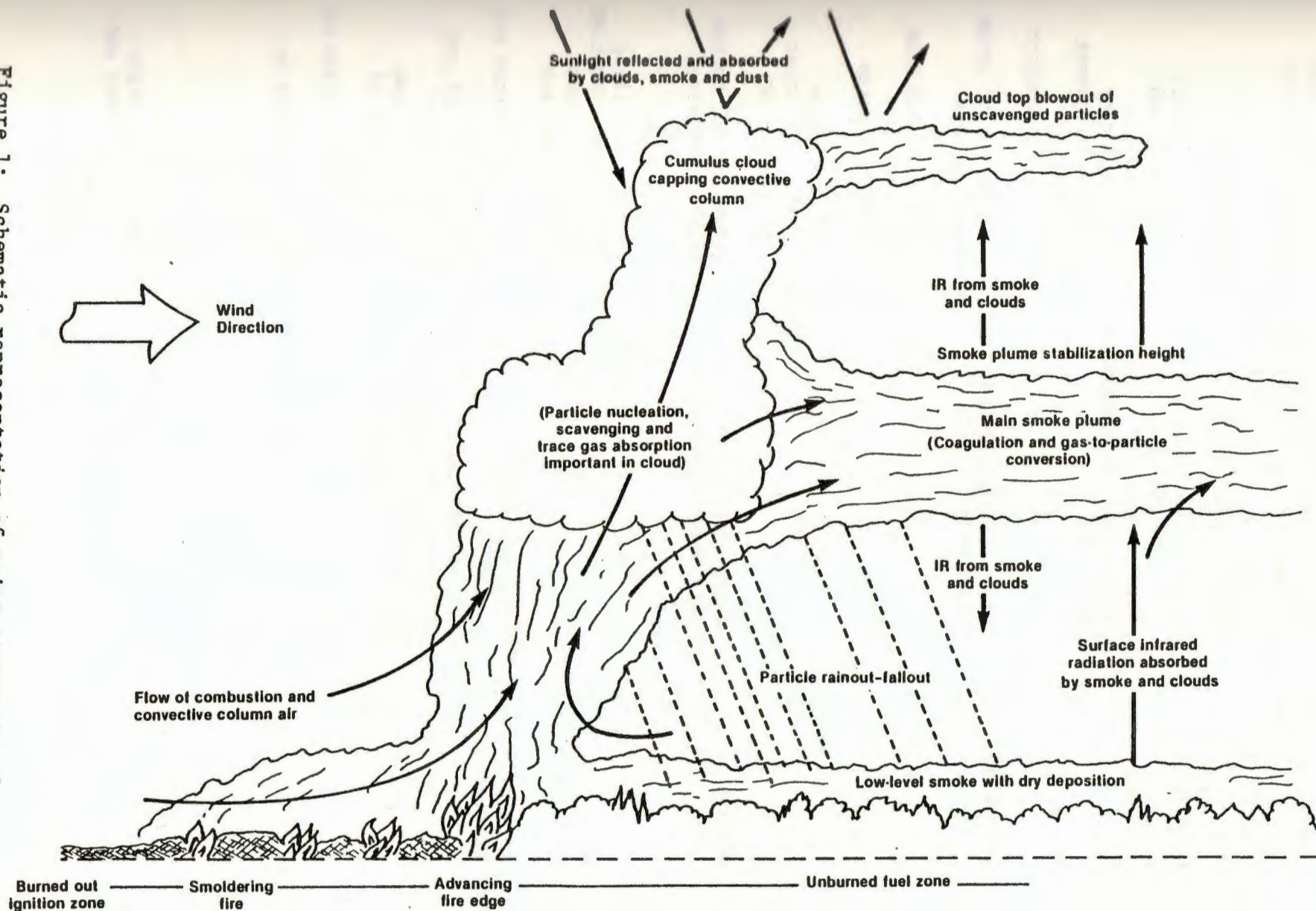


Table 1. Atmospheric Processes Important to Investigating Effects of Large-Scale Fires

<u>Component</u>	<u>Questions Addressed</u>	<u>Measurements</u>
Source Material	Amount of smoke and soot produced for a variety of fire sizes, intensities, and fuels	- o Ignition point fuel type and distribution - o Fire intensity - o Oxygen environment - o Ventilation - o Thermal environment
Properties of Smoke	Level of infrared and visible extinction	- o Composition of smoke - o Smoke optical properties - o Smoke mass and size distribution - o Scattering phase function - o Particle shape - o Infrared and solar optical depths
Plume Dynamics	Height of plume; Entrainment processes	- o Plume top and bottom - o Ambient humidity, winds, and temperature - o Vertical stability - o Altitude of formation of water clouds - o Plume velocities
Cloud Interactions and Removal Processes	Extent to which smoke and clouds interact; Degree of scavenging; Rates of precipitation; Degree of coagulation	- o Smoke size before and after passing through clouds and precipitation - o Density and size distribution of particles - o Optical properties of soot - o Electric charge on cloud and precipitation particles - o Cloud drop distribution - o Cloud condensation nuclei in fresh and old smoke - o Ice nuclei

Table 1 (continued)

Smoke Cloud
Dynamic Interactions

Consequent radiative
effects and circulation;
Efficiency of clouds in
entraining air and dust;
Levels in atmosphere
where cloud would occur

- o Carbon soot size
and amount
- o Levels of turbulence
over fires
- o Direct measure of
visibility and
attenuation
- o Backscattering
coefficient

Thus the structure of the fuel molecules determines, in part, the emission of smoke.

The availability of oxygen in the early stages of fires is important in determining smoke yields. In enclosed fires, for example, the ratio of available to required oxygen levels needed for complete combustion can become quite small. There are two reasons for this: First, the oxygen supply must come through the available apertures (windows, doors, leaky seams). The resultant inefficient combustion causes the release of unburned hydrocarbons which condense to form smoke. Second, additional smoke and soot are generated by the acceleration of pyrolysis and incomplete combustion because of the elevated temperatures reached in enclosed areas. Conditions similar to an enclosed fire's increased smoke emissions might occur in the centers of large mass fires due to the inability of oxygen to penetrate effectively.

On the other hand, burnout of volatiles and carbonaceous residue, leading to a clean-burning fire, may take place, depending on the size of the burning area and on the intensity of the fires. For moderately low-intensity, individual fires, particle mass and character will be determined primarily by material type and ventilation effects. For larger and more intense fires with adequate ventilation from below, continued combustion may extend to considerable heights, allowing for a much more efficient burn.

There have been many laboratory and observational studies of smoke generation from various fuels. Some of these measurements also include assessments of the effects of flaming versus smoldering conditions. Other experiments have addressed some of the effects of oxygen-deficient combustion environments. Specific studies needed for evaluating the nuclear scenarios are inventory of fuel beds, particularly in urban areas (see, for example, Larson and Small, 1982) and theoretical assessments of smoke generation from mixed fuel fires, the relation of smoke emission from small-scale tests to

room-sized and larger fires, oxygen availability (which depends in turn on oxygenation level of modern urban materials, confined fire effects, blast enhancement of open fires, effects of asphalt and rubberized fuels, and ventilation effects in large fires), and the thermal environment and burnout in large-scale intense fires. These subjects are generally new areas in large-scale fire research although they conveniently build on existing programs and facilities.

The occurrence of firestorms during nuclear exchanges could lead to a significant enhancement of materials in the stratosphere. Appendix B notes that the range of fire particles propelled by firestorms into the stratosphere may be between 0 to 20% of the amount ejected into the atmosphere. However, the conditions under which firestorms occur are not fully understood. Efforts will be made to investigate the formation and effects of firestorms through modeling and controlled experiments, if appropriate.

Optical and Other Properties

The optical properties of smoke particles are critical to calculations of the climatic changes following a nuclear exchange since they determine the amount of sunlight and infrared radiation absorbed and scattered by the particles.

Some measurements have been made of the properties of smoke particles created in laboratory environments and in natural fires. For example, studies have been done on the optical absorption of soot produced by laboratory burning of pine needles. Others have measured the particle sizes and mass emission rates in a variety of small, prescribed fires in Washington and Oregon. Although such studies have limited the uncertainty attached to some properties of smoke, a number of significant questions remain.

Optical properties of smoke are sensitive to the fuel composition, fire temperature, fire ventilation, and degree of coagulation in the plume. Measurements have not been made in urban fires, where many synthetics are present, or in very large forest fires. High smoke loadings in a large fire may lead to rapid coagulation and growth into large particles with small optical cross-sections. On the other hand, coagulation may not be significant or it may lead to differently shaped particles with different results. The scattering and absorption properties of aerosols are determined by their chemical composition, the particle size distribution, and to a degree, by particle shape. There are large differences between theoretical and observed properties of particles in plumes. Sufficient radiation measurements using state-of-the-art instruments have not been made.

Theoretical calculations predict that a water cloud containing even small amounts of soot can effectively absorb sunlight. The heating might act to dissipate many clouds before they are able to precipitate or before they could enhance convection, precipitation, and soot removal.

In order to resolve these questions, the composition of the smoke and the smoke optical properties need to be determined for fires of different sizes, intensities, fuel compositions, and weather conditions. Direct data on the particle scattering phase function, on the optical depth for all wavelengths of the resultant cloud, and on the solar heating rates will improve our ability to calculate the radiative parameters of a dense smoke cloud of the type which may follow a large nuclear exchange.

The mass and size distribution of smoke particles in plumes must be determined in order to resolve the significance of coagulation and particle size and to better relate the super micron smoke mass to the mass of burned material. In this regard, it should be noted that recent measurements of

smoke particle size distribution from forest fires have shown that the super-micrometer particle mass in the range of 1-50 micrometers is comparable to the submicrometer mass. Large fires can be expected to produce millimeter-sized ash and debris in significant concentrations. This is important because these are often irregular, low-density particles with substantial residence times. If they become coated with water in a cloud, these particles are large enough to initiate coalescence and are subject to scavenging by rain.

A major factor in removal processes is the nucleation character of the particles or the coagulation of radiatively active particles such as elemental carbon particles with hygroscopic aerosol particles. These properties may be quite different for urban and rural fires. If a substantial amount of the material has either water or ice nucleation characteristics, it may contribute to its own washout, or conversely, to colloidal stabilization and reduced washout.

Because many particle characteristics depend strongly upon the fuel source and fire environment, studies of forest fires will not resolve questions about the optical properties of smoke from urban fires. It will be necessary to extrapolate laboratory data, or data from small burns of urban materials. A well-planned series of scaling experiments will be needed. Accompanying these must be a correlated development of the capability to predict the generation of particulates and condensible vapors from solid fuels and their evolution as a function of fire and atmospheric conditions.

Plume and Cloud Dynamics

The fraction of smoke that remains in the atmosphere and the rate of dispersion depend on interacting processes occurring on several scales. Plume and cloud-scale interactions on the order of 1 to 100 km are crucial in

several ways. The dynamics of plume rise and turbulent entrainment are important in the quenching of combustion, condensation of unburned pyrolysis products on smoke particles, and specification of the environment in which mature smoke particles grow through coagulation. Dynamics, especially wind shear and entrainment, along with atmospheric stratification, moisture profile, and fire intensity and extent, serve to define the plume stabilization height, which gives the maximum smoke injection altitude. This is a very important input in meso and large-scale models.

Numerous tested models for plume rise are available from such sources as volcanoes, smokestacks, and cooling towers. However, these models are not easily extended to urban or wild fires because of differences in sources, time and space scales, and injection products. In particular, the effects of atmospheric stability and convection, entrainment of ambient air by the rising plume, condensation of entrained or fuel-derived water vapor and release of latent heat, radiative heat loss from the flame, heat transfer from the smoke to the gas, and the effects of vertical shear in the ambient wind, all pose complexities which tax even the most sophisticated current model. Because of all these uncertainties, some scientists believe that the smoke from large fires will be predominantly restricted to the troposphere, whereas others believe that some smoke will rise rapidly into the stratosphere, where much of it may remain for several months and some of it up to several years.

Plume models could be improved by additional field observations. To resolve some of these questions, it would be desirable to measure the top and bottom altitude, the vertical distribution of the plume, and the downwind dynamics of plumes from a variety of fires as a function of energy release rates. The dependence of these quantities on areal extent and fire intensity, ambient humidity, and ambient wind field must also be determined. The degree

of air entrainment and the heat radiated by the fire must be measured, since they are not easily calculated from first principles. It is also necessary to measure the altitude of formation of water clouds in these plumes, to relate the horizontal location of the water cloud to that of the plume, and to relate the region of precipitation to the region in which the plume is located.

Analyses of past experiments will help in understanding the entrainment process. Some of these experiments are large-scale convection experiments in which Doppler radars were used to map the three-dimensional kinematics of isolated convective clouds. Smaller scale, but more intensely buoyant experiments have been performed using oil burners distributed over a large grid exceeding $10,000 \text{ m}^2$. However, reduction and analysis of experimental data in these experiments was not comprehensive and therefore these or similar data must be more fully analyzed to acquire an adequate model of turbulent entrainment. If fires of opportunity, such as large urban, grass, or forest fires, could be studied adequately on short notice, they would provide additional understanding of entrainment processes.

Plume dispersion will also be affected by solar heating and processes acting on mesoscales of 10 to 1000 km. The extent to which solar heating in dense plumes induces mesoscale or large perturbations needs to be determined. Plumes may be buoyant even far downwind from a fire because of solar heating or because they are negatively buoyant due to infrared cooling. This may cause the plumes to rise as they are advected downwind. By contrast, inhomogeneities in the plumes may lead to the development of small-scale convective cells. Potentially, these cells could mix the materials vertically and/or induce condensation and precipitation, which might lead to smoke removal. It is also possible that the reduction of solar heating below the plume will stabilize the lower atmosphere and reduce convection. Careful

study of the vertical dynamics of plumes is likely to be fruitful for only large fires, and could be measured by coupling lidar observations of the plume with the meteorological information available from aircraft sensors.*

The dynamics of plumes should depend primarily upon properties which are relatively independent of the fuel source. Hence, measurements made in large forest fires are likely to be directly relevant to the plume dynamics for large urban fires, provided they are of comparable geometry and intensity. These measurements should provide a good verification test for models of plume dynamics.

Cloud Interactions and Removal Processes

A complicated process which needs to be better understood is the interaction between precipitation and smoke, since the residence time of the smoke in the atmosphere may be largely controlled by precipitation. Smoke will often interact with fire-capping clouds where the ratio of cloud mass to smoke is about $10^4:1$. In these cases, clouds control the initial injection properties of the smoke and its eventual removal. Many of the effects described in table 1 also depend on the microphysical character of clouds and aerosols and on the atmospheric conditions at the time of the fires.

Smoke-cloud interactions have two parts. First, the removal of smoke by precipitation may be size selective and sensitive to the chemistry, electric charge of the smoke particles, and the electric fields within the cloud. Second, the smoke may modify the clouds either directly by changing the

* Historical fires may also provide evidence of the climate changes occurring beneath dense soot clouds. Past accounts of atmospheric effects associated with the large wild fires of 1871, 1910, 1930s, 1950, 1951, 1971, the Siberian peat fires early in this century, and the Australian fires of 1982-83, and others require detailed evaluation.

ambient concentrations of cloud nuclei and the cloud's optical properties, or indirectly by modifying atmospheric temperatures and wind fields which control the formation of clouds.

In order to better understand these problems, several different levels of experiments are needed. Laboratory studies will be particularly useful in determining the coagulation characteristics of soot particles and the efficiency of these particles in acting as nucleating sites. In the field, some work has been done to measure particle sizes before and after the smoke from a fire has passed through a cloud. Simultaneous measurements are needed of cloud drop distributions to determine how the smoke has modified the cloud microphysics itself.

Recent theoretical and experimental studies suggest that the presence of electric charges may have a large impact on coagulation of soot and particulates and on the collection of these by cloud and precipitation particles, thereby significantly influencing their ability to remove aerosol particles from the atmosphere. It is likely that the nature of the electric fields normally present in the atmosphere would be altered by nuclear explosions and that increased ionization of particles might occur. Previous atmospheric tests created strong ionization on a hemispheric scale; however, this effect may be countered by the presence of large amounts of smoke, which decrease ion mobility. The extent to which electric charges are important for the "nuclear winter" hypothesis needs to be determined.

Well-planned measurements in conjunction with large field fire experiments will include direct sampling by ground towers or aircraft (preferably helicopters) using particle counters. Sample gathering by high-volume impactors will allow laboratory determination of complex refractive indices and nucleation activity. A direct measurement of visibility and hence

its alteration can be obtained by tower-mounted lasers or by using the sun as a source. Remote sensing by multiwavelength, ground-based lidar can provide estimates of the size distribution and the backscatter coefficient.

Finally, sooty smoke may not be removed efficiently until photochemical reactions in the atmosphere start the process to deposit soluble materials, such as sulfate, on the soot surfaces. To test this point, the number of cloud condensation nuclei in fresh smoke clouds must be measured. Since smoke is not pure carbon, and since winds may lift much organic and soil material from the surface, there could be abundant condensation nuclei in the fire plumes, as is commonly observed in prescribed and wild fires. The nucleation capability of fresh smoke must be contrasted with that of aged smoke and soot to determine if background photochemical processes make the smoke more susceptible to removal by rainfall.

In addition to determining the particulate properties of fire plumes, the particulate loading in the background atmosphere must be characterized for two reasons. First, the amount of smoke and soot in the ambient atmosphere is not known, either in that half of the earth's atmosphere over the tropics where burning seems to be concentrated, or in the arctic, where observed aerosol containing soot is unexpectedly large. Soot may already play a larger role in the earth's heat budget than has been expected. A better definition this role might allow experimental insight into the interactions of soot with the climate.

Second, the concentration of soot in the tropics results from the mingling of emissions from many different fires as well as from interactions with precipitation processes. An understanding of how the natural processes control the amount of soot can provide a basis for understanding how the process might function after a nuclear exchange.

In order to gain this understanding, it is necessary to obtain better estimates of the number of global fires. This might be done in part from analysis of satellite data currently being gathered or by making field measurements of fires and the amount of soot and smoke generated, its injection altitude, and the amount typically present in the atmosphere.

The existing dry and wet deposition stations of the acid rain network may be able to provide, by additional analysis, estimates of soot removal processes. This information should also help in estimating the efficiency with which rainfall removes smoke from the atmosphere.

Most of those processes having to do with the interaction between smoke and clouds may not depend strongly on whether the smoke is generated by an urban fire or by wild fires, but will depend on injection altitude. Exceptions may be particle size and the abundance of cloud nuclei or the water-soluble nature of the smoke. Data from laboratory and small urban fires will be used to extend atmospheric measurements on wild fires to the urban mass fire case. The drafting committee underscores the important role and need for fire, plume, convection, and microphysical models in planning field and laboratory experiments.

Atmospheric Chemistry

Natural fires may be major sources of NO_x , $\text{C}_2\text{-C}_5$ hydrocarbons, CO, and several other gases. These gases are currently of critical importance to the chemistry of the troposphere. Crutzen and Birks (1982) estimated that the fires following a nuclear exchange might triple the amount of CO in the global atmosphere and inject an amount no larger than that from the nuclear fireballs and equivalent to the entire current annual input of NO_x . Originally Crutzen and Birks suggested that these emissions could significantly alter the ozone

budget of the troposphere, yielding widespread smog and surface ozone levels that are potentially lethal to some vegetation. Those ideas were based on the presence of high levels of oxidants which are generated photochemically. The presence of large quantities of light-absorbing soot may prevent these oxidants from being initially produced (Penner, 1983).

With one exception, past studies of the effects of a nuclear war on the stratospheric ozone layer have relied on one-dimensional eddy diffusion models, and none of these models has included dynamic feedbacks. Furthermore, no self-consistent attempt has yet been made to treat this problem in concert with the temperature and dynamic changes that would result from large injections of dust and smoke. The extent to which the ozone layer is depleted and the time it takes to return to normal have been shown to be highly scenario dependent. The larger the yields of individual warheads, the greater the effect on the ozone layer. However, there remains about a factor of two in the uncertainty of the amount of nitrogen oxides (the ozone depletion catalyst) produced per megaton of explosive yield. This uncertainty results from the lack of precise knowledge of the temperature history of air entrained by the fireball and could be reduced by incorporating reaction kinetics in present fireball models.

Besides the catalytic effect of oxides of nitrogen, ozone depletion could result from the attenuation of solar ultraviolet light and from increased temperature due to highly absorbing smoke aerosols in the stratosphere. Such measurements can be made part of the overall fire source experiments. A complete assessment of the ozone layer problem must include two- and three-dimensional models of coupled atmospheric radiation, dynamics, and chemistry. Several such models are at various stages of development.

It has been suggested that a nuclear war could result in an intense photochemical smog with sufficiently high oxidant levels to damage the biosphere throughout much of the northern hemisphere. This could not occur in the absence of sunlight, but only after most of the soot has been removed by wet and dry deposition processes. The extent to which a photochemical smog would occur is highly dependent on the removal rates of atmospheric species in the perturbed atmosphere and on patchiness of smoke. The reduction of oxidant concentrations during the initial darkened period would tend to enhance the lifetimes of many species and allow the further accumulation of reduced compounds such as hydrocarbons, terpenes, and the sulfur compounds emitted by the biosphere. On the other hand, NO_x may still be efficiently converted to the nonphotochemically active form HNO_3 , potentially reducing smog formation.

As part of the chemistry and fire experiment research, an assessment of possible toxic gases released particularly from the burning of synthetics could be determined. A number of these substances have been identified, including carbon monoxide, cyanide, dioxins, and furans. The introduction of these gases may be a major additional hazard of nuclear war. Efforts to understand these pyrotoxins is a natural concomitant of some of the proposed fire research and could be studied in this context.

Before the full tropospheric response can be evaluated, both field and laboratory data must be obtained. Laboratory studies of heterogeneous reactions are especially needed. These types of studies are a new field of investigation for which new techniques are currently being developed. Work in this area has been spurred by acid rain studies. Kinetics studies using flow tubes coated with smoke aerosols of various compositions could be utilized to determine the reaction efficiencies of oxidants such as OH , HO_2 , and O_3 with aerosol surfaces. Similar measurements on sulfuric acid surfaces have been

made in the past. Such reactions could be important in reducing oxidant concentration as well as in oxidizing the particle surfaces so as to render them more hydrophilic and susceptible to removal by wet processes.

Complementary studies will be carried out on suspended aerosol particles of varying type and composition. The removal of gaseous species by adsorption on aerosol surfaces will also be studied in this way.

While emission factors for species such as carbon monoxide, nitrogen oxides (NO and NO₂), and many organic compounds have been measured for a few forest fires, this data base needs to be expanded and emission factors and pyrotoxins determined for fires more characteristic of cities.

4. LABORATORY AND FIELD EXPERIMENTS AND ANALYSES

The goals of an experimental plan designed to address the issues discussed in section 3 are summarized in table 2. Because so many different kinds of measurements are required, laboratory and field experiments must be carefully planned to maximize the information content. Since the problem itself can be treated only by extrapolation or modeling, the field experiments must be planned jointly by theoreticians and modelers.

To properly understand the scaling relationships needed for assessing nuclear scenarios, a range of fires of varying intensities and fuel types must be studied for principal fuel bases in urban and wild land. Intrinsic differences between urban and nonurban fires require different approaches. In the nonurban case, it will be possible to focus on the yearly managed fires, directly measuring fuel type and composition, and using aircraft to assess smoke quantity and character.

The lack of a similar opportunity to observe large-scale, intense urban fires suggests a different approach. Instead of an experimental focus on the few largest urban fires, it will be more appropriate to develop a more finely resolved set of laboratory scaling experiments, from bench size to multistructure, effecting the development of confidence in the extrapolation from small to large-scale urban fire effects.

These separate approaches are complementary. Phenomenology acquired from the smaller scale urban-focused experiments will be applicable to nonurban fires. Similarly, it should be possible to apply much of the information on the effects of large wildland fires to the large-scale urban fire environment.

Table 2

Goals of Experimental Program

1. Determine how the gas and particulate yields and properties depend on fire and fuel characteristics. Quantitative scaling rules must be developed to relate variables to these characteristics.
2. Quantify and characterize the properties of the particulate and gaseous emissions from fires.
3. Determine how meteorological parameters affect flammability, fire spread, fire intensity, particle properties, and plume heights.
4. Quantify the interactions between fires, smoke, clouds, and precipitation. These interactions will be on two time scales: prompt effects with highly concentrated smoke and fire-capping cumulus clouds and delayed effects in "ambient" clouds.
5. Determine the ambient smoke levels in a region with many natural sources, such as the tropics, and determine the number of active sources. Quantify the interactions of emissions, multiple sources, and removal processes in order to calculate the regional smoke concentration.
6. Experimentally determine the dynamics of a variety of buoyant plumes in order to both test and constrain plume models.
7. Measure the radiative properties of an array of dense smoke plumes for direct comparison with calculated characteristics based on particle measurements.

Nonurban

Proper source function characterizations require a range of fire size intensities and fuel types. A variety of planned fires will be identified through contacts with the U.S. Forest Service, and the forest services in other countries. For example, the United States and Canadian Forest Services burn large areas each year and very large fires are set in many tropical countries. Efforts will be made to have these groups, or others, start moderate-sized mass fires as well as smaller fires with a variety of fuel sources. Although the initial experiments may be conducted in line fires, it is hoped that the opportunity will develop to study mass fires with multiple ignition sources.

Location, size, and the experimental focus of these wildland fires all argue that the principal measurements should be made from airborne platforms. A model for the experimental design, observations, and equipment needed for these studies is shown in figure 2 and included in table 3. This work is directed at defining the relationship between observed fuel density and composition, fire size and intensity, and the following features:

- o Plume Dynamics: Measured by nearby and more remote observations of vertical and horizontal dynamics, the plume temperature structure, ambient temperature and moisture structure, plume morphology and entrainment measurements
- o Smoke Quantity and Character: Measured by specific gas detectors and a variety of passive and active particle sampling techniques
- o Smoke Optical Properties: Determined from passive visible and infrared

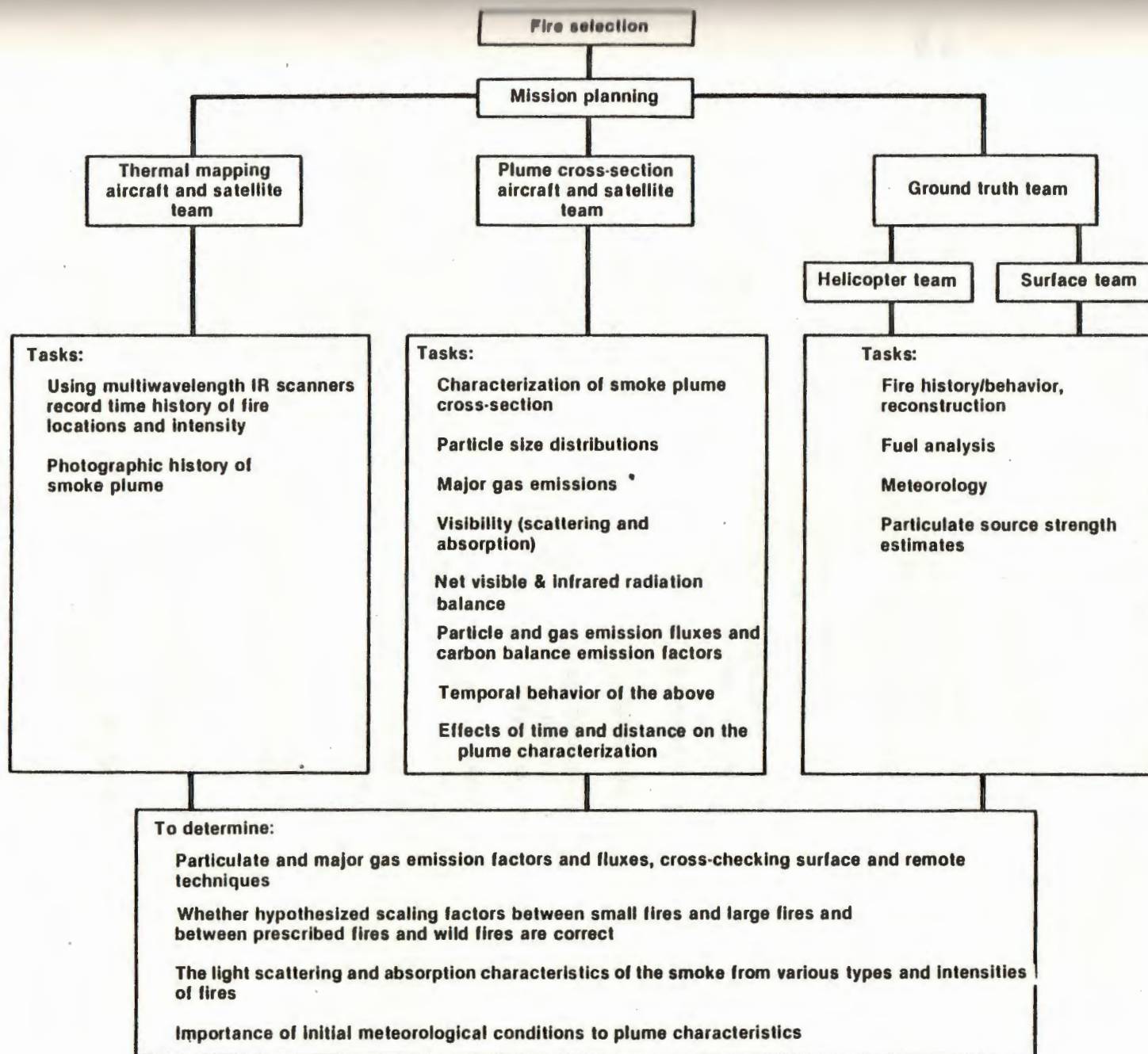


Figure 2: Initial concept for conducting fire experiment operations and measurements.

Table 3. Parameters to be Measured*

<u>Parameter</u>	<u>Instrument</u>
Local dynamics (vertical updraft in plume, induced winds)	Meteorological boom on aircraft Doppler radar and doppler lidar
Air temperature, plume temperature	Aircraft thermistors
Plume top, bottom altitude, vertical distribution, and downwind extent	Fast-response particle size detector, lidar, or conden- sation nuclei counter, cinematography
Degree of plume mixing with ambient air	Passive tracer
Fire intensity measurements	Ground-based temperature, airborne spectral scanner
Radiative flux	Flux meter
Fire area	Spectral scanner
Particle mass loading integrating nephelometer, microbalance impactors	Filters, fast response
Smoke composition and vertical distribution	Impacter collections, filter collections
Smoke particle size and morphology	Particle sizing instruments, multiwavelength imaging probe
Smoke optical properties, scattering phase function	Filter collections with laboratory analysis, scatterometer
Smoke visible & infrared optical depth	Sun photometer, infrared photometer
Atmospheric heating in smoke cloud	Flux measurements at several altitudes

* Multispectral satellite data are useful in determining many of the above parameters.

Presence of H₂O cloud
and characteristics

Cloud particle size,
spectrometers

Cloud removal efficiency
for smoke

Particle size

Gaseous emissions
special sensors

NDIR gas chromatographs,

photometry, measurements of individual smoke particle scattering phase functions, and if possible, from transmissivity measurements of filter samples

- o Capping Cloud Characteristics and Effects: Determine from measurements of cloud droplet size and concentrations, vertical variation of cloud interstitial aerosols and observations of cloud electric fields and particle and droplet charges

Finally, a set of smoke and soot measurements in the tropical atmosphere remote from fire plumes should be made. These measurements could be related to satellite observations of the number and extent of fires throughout the tropics during the several weeks preceding the experiment. The measurements could determine the effects of multiple fires in producing a uniform smoke pall and the scavenging effect of the precipitation. Measurements of soot in commercial aircraft corridors would also be valuable for understanding budgets of high-level soot injection into the atmosphere.

Urban

Both laboratory and large-scale controlled experiments for a variety of structures and urban conditions will be planned to determine the quality and character of emissions from homogeneous and mixed fuel fires. Specific laboratory experiments on urban material will address the basic questions of:

Smoke production for mixed fuels

Degree of coagulation of submicron soot particles

Efficiency of soot particles as nucleating sites

Optical properties of nonspherical smoke and soot particles
Degree of gas-to-particle conversion

It is of interest to know whether the initial states of confined fires might produce significantly more smoke before they break through the structure and become open fires. Laboratory experiments will investigate this effect by controlling the oxygen level of the fire environment. If these experiments suggest that these effects are significant, then larger, more complex experiments will be explored.

The primary issues with respect to urban fires are whether large-scale intense fires are more or less efficient and therefore produce more or less smoke for the same mass of fuel consumed than do smaller, quieter fires, and whether firestorms form.

To study this question, a series of indoor, controlled experiments of varying scales will be planned, to see whether soot and aerosol emission factors can be empirically scaled to larger-sized fires. The effects of nearby heat sources (i.e., other burning structures) will be investigated as well as the effects of oxygen availability and burnout. To integrate these effects into a coherent picture of a mass urban fire, models of soot and smoke formation and near-fire dynamics must be developed. These models will be validated by various scales of controlled experiments.

Once there is confidence in the predictability of emissions from larger scale fires, a set of structure fires will be planned. These will allow at least one check on validity of the scaling experiments described above. However, relating the emissions from a single structure fire to those expected in a large mass fire will require models that can predict the oxygen and thermal environment near the smoke formation region. The development of these

models must be linked to the smaller scale experiments described above in order to be credible. Fire model research must be planned in parallel with fire experiments to ensure maximum application of the experiments.

Fire Rapid-Response

It may be possible to take advantage of unplanned urban or vegetation fires if such fires can be immediately recognized and if an observational program can be organized to respond rapidly. Both the NOAA polar-orbiting and geostationary satellites are capable of detecting fire plumes and smoke areas. In addition, the 3.8 micrometer channel on board the polar-orbiting satellites can detect the fire areas or so called "hot spots." Maximum resolution on both satellite systems is 1 km but most operational data are at 4 km. Even at this resolution, fire activity is easily seen on satellite imagery (see figure 3). Forest, rangeland, tundra, and slash-and-burn agriculture fires have been detected with the NOAA satellite data and are available in digital or image format from the NESDIS satellite archive. Some of the forest and tundra fires in Siberia and Canada have generated smoke that covered areas as large as 50° longitude x 5° latitude (approximately 1.5 million km^2) and that lasted as long as three weeks. Visible and thermal infrared satellite data in conjunction with conventional data can provide information on fire source areas, fire spread, smoke flow, smoke altitude, smoke area, smoke residence time, radiation balance effects, and smoke opacity. Use of multispectral data on the polar-orbiting satellites may also provide information on smoke particulate sizes.

The reduction in solar radiation at the earth's surface due to large fires can be directly measured by existing solar radiation networks located at 34 meteorological stations in the United States.



Figure 3: NOAA-7 imagery detected several large smoke plumes in Siberia from 10 to 25 July 1984.

Federal agency and university scientists were able to respond rapidly to the eruption of Mount St. Helens and organize an observational program to measure and track the volcanic plume. Based on this experience, it is likely that a similar rapid response can be organized for a major fire, at least in the United States.

Other Experiments and Related Studies

Many of the climate effects following a nuclear war involve large-scale radiative interactions between aerosols and the atmosphere. Of course, there are no events in nature which duplicate these effects exactly. However, large dust storms such as those that occur continually over the Sahara desert may serve as a limited natural analogue of smoke produced by nuclear exchange. For example, Brinkman and McGregor (1983) report dust storms over Nigeria with optical depths up to 2, reductions in total solar radiation of 28%, and temperature decreases as large as 6°C. The qualitative similarity with the nuclear winter scenario suggests that these dust storms might usefully be sampled and modeled.

Because of the high altitude and high albedo of the dust, it can greatly enhance the effects of the soot clouds below. A wide range of dust studies are possible, including dust generated in test chemical explosions; new studies of archived particles sampled from above-ground nuclear weapons tests, and flights through future dust clouds.

Experimental studies could presumably be conducted using standard radiosonde stations to collect information on atmospheric temperatures as well as instrumented aircraft to measure the altitude and extent of the dust cloud, the cloud particle properties, and the radiative fields. There are, of

course, no direct analogues of nuclear explosions. Yet these analogues are useful in testing some aspects of climate simulations. Other possible naturally occurring analogues for assessing the nuclear effects are summarized in table 4.

Table 4. Analogues*

<u>Process</u>	<u>Analogues</u>	<u>Relevant observations</u>
Soot particle source function	Urban fires (Moscow, 1812) San Francisco, 1906, etc.) World War II firestorms from conventional bombing (Dresden, Hamburg, Tokyo) and from atomic bombing (Hiroshima, Nagasaki) Tropical slash-and-burn agriculture Historical forest fires Bush fires Arctic haze Land-clearing open fires Deliberate experiments (smoke pots, burning vehicle hulk, carbon black dust)	Total particle mass, Particle size distribution, Vertical distribution, Horizontal distribu- tion, Optical properties of particles, if available
Dust particle source function	Volcanic eruptions African dust storms Arctic haze Battlefield dust experiments Road dust	(Same as soot particles)
Atmospheric dynamic response	Martian dust storms	Decreased baroclinicity Induced cross- equatorial transport
Hydrological cycle	African dust storms	Decreased convection

Climate response	Asteroid impact 65 million years ago and other apparent impact-induced extinction events	Extinction of dinosaurs and many other species, presumably from surface cooling and darkness
	Seasonal cycle	Summer to winter change in forcing and temperature response about the same as nuclear winter scenarios, but slower
	Diurnal cycle	Day to night change in solar energy forcing and surface temperature response similar to some nuclear smoke scenarios
	Saharan dust	Reduced surface air temperature
	Great Smoke Pall (Canadian forest fires - 1950)	Reduced daytime surface air temperature
	Volcanic eruptions	Immediate surface air temperature response (cooling day and night - Krakotoa, cooling during day and warming at night Mt. St. Helens)
		Rapid (1 to 2 months) cooling over continents
		Hemispheric cooling with maximum amplitude in winter polar regions 2 and 3 years after eruption

Table 5: Summary of Cloud-Scale Models Active in 1980

Model Identification	Domain	Emphasis	Contact	Remarks
<i>One-Dimensional Steady-State Models</i>				
BUREC	20 km (vertical)	Cloud top, vertical motion, seeding potential	Matthews	
SDSMT	20 km (vertical)	Cloud top, vertical motion, seeding potential, plume transport	Hirsch, Orville	Used for maximum hailstone size prediction
NOAA/ERL	20 km (vertical)	Cloud top, vertical motion, seeding potential	Woodley	Used to predict covariates in weather modification project
CSU/1D	20 km (vertical)	Cloud top, vertical motion, seeding potential	Cotton	
<i>One-Dimensional Time-Dependent Models</i>				
SDSMT	20 km (vertical)	Cloud microphysics, hail prediction	Farley, Orville	
<i>Two-Dimensional Models</i>				
U. Ill./2D	48 km x 14 km	Single clouds, severe storms	Soong, Wilhelmson	Axisymmetric and slab symmetric models
U. Wisc./2D	~50 km x 15 km	Severe storms	Schlesinger	Liquid bulk water microphysics, slab symmetry
CSU/2D	35 km x 17 km	Tropical Cu, mountain Cu	Cotton	Slab symmetry
NCAR	18 km x 12 km	Detailed cloud microphysics, ice and liquid processes	Hall	Slab symmetry
SDSMT/2D	20 km x 20 km	Hailstorms, cloud electrification, cloud modification	Orville, Farley, Helsdon	Some detailed ice microphysics, slab symmetry
Hawaii/2D	6 km x 6 km	Detailed microphysics, hailstone growth, cloud electrification	Takahashi	Axial symmetry
RAND	10 km x 10 km	Tropical Cb, ice bulk water microphysics	Murray, Koenig	Axial symmetry
U. Wash./2D		Detailed microphysics, particularly ice phase	Hobbs	Axial symmetry
<i>Three-Dimensional Models</i>				
U. Wisc./3D	48 km x 48 km x 14 km	Severe storms	Schlesinger	Liquid bulk water microphysics
CSU/3D	35 km x 35 km x 17 km	Tropical Cb, mountain Cb	Cotton	Some ice bulk water microphysics
NCAR/III./3D	48 km x 48 km x 16 km	Severe storms	Klemp, Wilhelmson	Liquid bulk water microphysics
NCAR	50 km x 50 km x 15 km	Hailstorms	Clark	Liquid bulk water microphysics
NCAR	10 km x 10 km x 17 km	Tornado genesis	Rotunno, Klemp	Nested in 3-D cloud model
Hawaii/3D	6 km x 6 km x 4 km	Tropical Cu, detailed liquid microphysics	Takahashi	
NOAA/GFDL	3 km x 3 km x 2.5 km	Tropical Cu	Lipps	Liquid bulk water microphysics

5. IMPROVEMENTS IN MODELING ATMOSPHERIC PROCESSES

Radiation

Particles in the atmosphere directly affect the earth's climate by interacting with solar and thermal radiation to alter radiative heating rates within the atmosphere and at the ground. These changes in heating rates can lead to modification of temperature, precipitation, and wind fields and are crucial in defining the potential climatic disturbance caused by nuclear war-generated aerosols.

Detailed radiative transfer calculations have provided the approximate magnitude of the change in atmospheric heating rates for plausible properties of the smoke and dust particles that might be produced in a nuclear exchange. If large amounts of carbon smoke are injected into the middle and upper troposphere and lower stratosphere, these atmospheric layers would experience a large increase in the solar heating rate. The land surface below, deprived of much solar radiation, would initially experience a cooling. Heating in the troposphere would be due chiefly to the absorption of sunlight by the smoke; cooling at the surface would be due to reduction in sunlight reaching the ground. A warming of the lower stratosphere and a cooling of the entire troposphere may characterize later times when most of the smoke has been removed from the troposphere but dust and some smoke remain in the lower stratosphere.

Published estimates of the radiative effects of nuclear exchanges have provided rough estimates under different scenarios and assumptions. The major uncertainties in these estimates result from a lack of direct measurements of radiative properties and effects of smoke aerosols. Major radiative

properties directly determining the alteration of heating rates include (1) visible and infrared optical depths (a measure of the probability of particles interacting with light), (2) single scattering albedo (ratio of the scattering cross-section to the sum of the absorption and scattering cross-sections), and (3) scattering phase function (probability of radiation being scattered in various directions).

A significant improvement in understanding the radiative effects of nuclear exchanges could be obtained by directly measuring the radiative characteristics of smoke aerosol during proposed fire source experiments. Such measurements should be taken close to the burn as well as far downwind. Concurrent measurements of the pre-burn characteristics of the fuel source and fire intensities as well as related size distribution and composition would provide a basis for parameterizing the radiation effect.

A problem which has not yet been addressed by climate models is the nature of the modification in the radiative properties of water clouds engendered by smoke. This is a potentially important problem in view of the central role precipitation plays in removing smoke particles from the atmosphere and in view of the possible alterations of the precipitation character of clouds that could follow from changes in the radiative properties. While this problem is more difficult to address experimentally than that of the radiative properties of the smoke particles, initial estimates can be made by measuring the size distribution, composition, radiative properties, and radiative heating rates within the water clouds that frequently cap fire plumes or within water clouds that may form in the smoke plumes of large forest fires.

While high resolution radiative transfer algorithms have been used in one-dimensional, radiative-convective models, a less complete treatment of

radiation has been used in calculations made with dynamic models. Since dynamic models, especially global and mesoscale models, will play a central role in future attempts to improve the estimates of the climatic effects of nuclear war, high priority must be placed on incorporating fast, yet accurate and complete radiation algorithms into these models.

Radiative transfer codes used in studying the aerosol problem relevant to the nuclear war scenario should be tested by comparison with other similar codes. Radiative transfer codes could be tested in isolation by using a standard aerosol configuration including solar scattering and infrared absorption.

Much of the evaluation of atmospheric effects of nuclear war depends on modeling atmospheric processes on a variety of spatial scales. Three major scales of interaction are plume-cloud, 1-100 km; mesoscale, 100-1000 km; and global, greater than 1000 km.

Plume and Cloud Interaction Modeling

Plume-cloud models are essential for two reasons:

The lifetime of smoke in the atmosphere is determined primarily by the initial height of injection and by precipitation scavenging that requires modeling of the spatial scale of individual clouds and ensembles of clouds and synoptic scale systems. Surveying in the initial plume should be considered as well as longer term scavenging on the larger scale.

The effect of smoke and dust on clouds and precipitation and therefore on vertical and horizontal transport needs to be parameterized for use

in large-scale climate models that cannot explicitly resolve individual clouds. Also the effect of clouds and precipitation on smoke and dust needs to be parameterized for large-scale models.

A major effort in calculating local-scale circulation in conjunction with the evolution of aerosol microphysics is also needed. Plume and cloud models have been developed for many applications, but some further modifications are needed for application to the nuclear war problem.

Microphysical questions that need to be considered include (1) overseeding, (2) changes in aerosol characteristics due to passage through nonprecipitating clouds, (3) effects of aerosols on precipitation formation, (4) importance of attachment of aerosols to droplets, (5) how smoke particles compete with natural aerosol as condensation nuclei, (6) freezing nuclei, (7) how ice phase evolution is affected by smoke and dust particles, and (8) whether the presence of ice affects scavenging rates and efficiencies.

Plume models are primarily one dimensional. Some involve cloud processes and would be appropriate for predicting cloud top heights and the height to which pollutants would rise. Similarly, one-dimensional cloud models offer a way to analyze atmospheric soundings to determine the depth of convection to be expected. Such models have been used extensively in cooling tower problems. Extreme heat and vapor inputs could be tested for their effects on convection. The efficiency of one-dimensional models would allow many different soundings at many different places and times of the year to be used to predict the penetration height of clouds of various widths.

Multidimensional, time-dependent, plume-cloud models are needed to attack the aerosol-cloud interaction problems mentioned above, as well as the cloud venting and overshoot problem. Some of the various cloud models in both two

and three dimensions which are available are given in table 5, which is taken from the National Academy of Sciences report (1981). Some of these models treat both ice and water microphysics; some include many particle sizes, allowing for the evolution of the drop size distributions, while others have highly parameterized microphysics and assume a typical size distribution. Some of the models allow for aerosol fields and simulate interactions with the motion fields. Cloud model grid intervals vary from 100 to 1000 m; domains vary in the vertical from 10 to 20 km and in the horizontal from 10 to 100 km or more; some models have more complex turbulence formulations than others. Some of the models simulate heat fluxes and evaporation of water vapor at the earth's surface, which could be modified to simulate the much larger inputs to be expected from fires. These cloud-scale models need to be coupled with larger scale models in an interactive fashion to predict the spread of soot and dust or noninteractively to check for consistency among the predictions of the various scale models. A major review of existing cloud scale models is needed to assess their utility for evaluating the consequences of nuclear war.

Local-scale models fit in with the field experiments and are necessary to aid in the interpretation of the field observations. In turn, the observations are necessary to check the adequacy of the physics used in the models and to improve the models.

An overall integrated cloud modeling effort enhanced by new observations needs to be developed. An extensive computational study is needed of the washout capability and the venting properties of clouds under the extreme conditions resulting from a nuclear war.

Mesoscale and Global Effects

Theoretical analysis and preliminary model results indicate that large

amounts of smoke particles injected high in the atmosphere and spread over much of the globe have the potential for significantly reducing continental surface temperatures if the particles remain in the atmosphere for more than several days. It is the role of mesoscale and global circulation models to simulate the regional and global climatic effects of nuclear war-generated smoke and dust particles.

Mesoscale circulation models and global circulation models are fundamentally similar, differing primarily in horizontal resolution and the detail in which they treat atmospheric processes. Global models are designed to simulate the large-scale features of the entire global climate over time scales ranging from days to years. Typical horizontal grid resolutions in global models are 200 to 1000 km. Mesoscale models, typically used for weather forecasting and research, are usually applied to a bounded region of the globe (e.g., the eastern U.S.), and thus are used to simulate weather conditions for only a few days at a time. Global models, on the other hand, can represent many features of the present global climate with reasonable accuracy and are in a somewhat more advanced state of development than that of mesoscale models. However, mesoscale models trade simulation length and computational domain for enhanced horizontal grid resolution, typically 10 to 100 km. The increased resolution facilitates the simulation of meteorologically important features such as fronts and convective complexes. But neither type of model is yet well adapted for the large perturbations involved in nuclear war climate simulations. Similar enhancements are needed in both types of models, therefore the following discussion applies to both.

The principal physical processes which must be incorporated in a general circulation model for the study of nuclear winter are indicated schematically in figure 4. The portion of the figure above the dashed line shows those

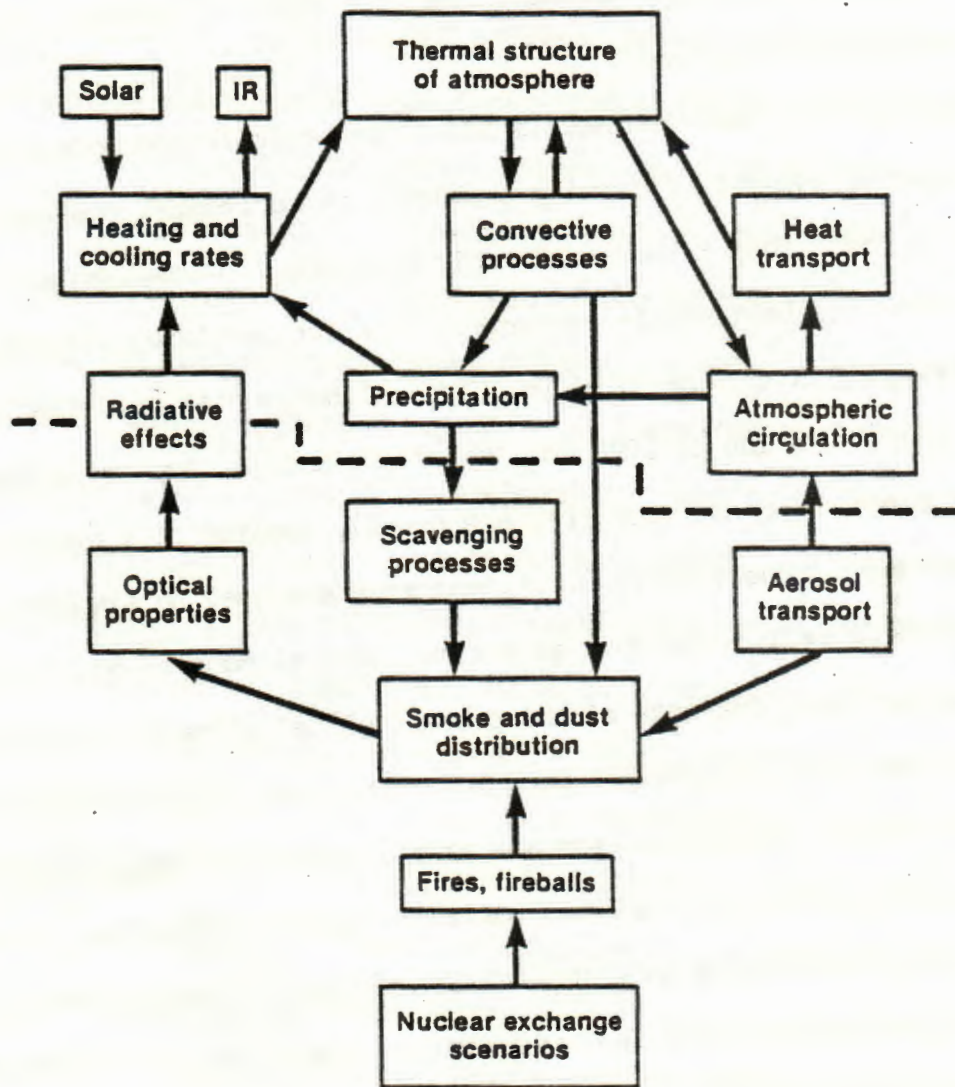


Figure 4: Principal physical processes required in global models to study the effects of nuclear explosions. Those processes above the dashed line are generally found in most global models; those below are not and require a concentrated effort.

processes which are found in global models designed for studies of the present climate. The physical processes in the lower half of the figure are pivotal to the effects of nuclear war but have generally received little study. Furthermore, because aerosols have a relatively small impact on the present climate, even for major injection events such as large volcanic eruptions, it will be difficult to test the validity of such processes with naturally occurring analogues. The paucity of relevant observational analogues will require greater than usual emphasis on stand-alone tests of the modeled physical processes. Also, transient regional-scale situations involving heavy aerosol loading, e.g., Saharan dust storm clouds, could provide some model validation.

Aerosols can be transported by subgrid-scale turbulent mixing processes ("convective processes" in figure 4). The most important such process is the vertical mixing resulting from turbulence driven by convective instability or wind shear. Because these processes occur on spatial scales which cannot be resolved by the coarse grid of a large-scale model, the resulting diffusive transport of various material properties must be parameterized. Because vertical turbulent diffusion may also be an important transport mechanism for smoke and dust particles, a more elaborate description of turbulent processes is required for studies of a nuclear winter than is presently available. For example, second-order closure models of turbulence are more realistic and detailed and are not highly "tuned" to the present climate, a frequent criticism of the application of global models to the nuclear winter problem. Fortunately, turbulent mixing processes are quite important for the unperturbed atmosphere, so the validity of these more sophisticated turbulence models may be assessed through benchmark simulations of the present climate.

Proper specification of the initial injection of smoke and dust ("fires,

fireballs" in figure 4) into the large-scale atmospheric circulation for use by global models is the major objective of the experimental program discussed in the preceding chapter. The effect of the fire source can also be investigated with a series of models: (1) combustion models on the scale of a single building; (2) multiphase reactive-flow models on the scale of several kilometers to study combustion efficiency, adequacy of oxygen flow to the fuel, soot production, and lofting; (3) cloud physics and plume rise models to study local precipitation scavenging in cloud-capped plumes; (4) multiphase fireball models to study lofting of dust in nuclear fireballs; (5) and mesoscale models to study transport, dispersion, and scavenging on scales out to several hundred kilometers and to study the effects of nuclear explosions, fires, and resulting clouds on the mesoscale atmosphere. At this largest scale, a spatial average of the smoke and dust distribution from these smaller scale models can be mapped onto the coarse grid of a global model to define the source term.

The efficiency of scavenging of smoke and dust by wet and dry processes is important on all scales. Treatments of scavenging processes must be included in most of the source-term models mentioned above. For climate consideration, the particles which interact with sunlight most effectively (per unit mass) are submicron; for such particles, removal by sedimentation is relatively inefficient. The principal mechanism for removal of submicron particles in the lower atmosphere is precipitation. Modeling of precipitation scavenging in both global and mesoscale models depends on: (1) prediction of precursor conditions for precipitation, (2) vertical and horizontal (subgrid) distribution of precipitation, (3) efficiency of removal of particulates, (4) proper simulation of precipitation-inhibition or enhancement conditions associated with the dense smoke and dust clouds themselves, (5) re-evaporation

and recycling of condensed material.

The first issue focuses on the ability of the model to simulate properly the upward flux of water vapor into the atmosphere and its transport to regions of large-scale uplift or convective activity, where it may be precipitated. A number of studies on precipitation climatology have been published, some with very successful simulations (e.g., S. Manabe and Hollaway, 1975). Simulated precipitation rates cannot be grossly in error since the latent heat release, which is an important atmospheric energy source, and the atmospheric dynamics, are often impressively simulated. Because the injection of smoke and dust and the major climatic impacts of a nuclear winter will occur over the midlatitude continents of the northern hemisphere, the outcome may be more sensitive to the distribution of precipitation than the average unperturbed climate.

Another problem in meso- and global scale modeling is determining the vertical distribution of latent heat release, which is important when aerosol scavenging is involved. The removal of aerosols in the atmosphere depends on processes in the troposphere and stratosphere. Even if a model were to predict the correct amount and geographical distribution of precipitation, in the lower troposphere the smoke and dust in the atmosphere will not be removed properly if the condensation is improperly distributed vertically or horizontally in the troposphere. Experimental results have generally shown a high scavenging efficiency for particles injected into the region of precipitation formation. However, scavenging efficiency parameterizations that are based upon observed aerosol residence times in the unperturbed atmosphere are inappropriate, since they implicitly assume the present vertical distribution of temperature, moisture, clouds, and precipitation formation.

After the initial injection of aerosols by nuclear explosions and fires, dense smoke clouds may modify the atmosphere in ways which could inhibit scavenging of the smoke. If the troposphere was stabilized by a combination of heating in the smoke clouds and (land) surface cooling, convective processes and the upward flux of water vapor from the surface could be inhibited over land resulting in greatly reduced convective precipitation. It is less clear what might happen over the oceans, where the surface temperature will be relatively unchanged. It also remains to be seen what role regional and continental scale inhomogeneities in the smoke cloud will play in generating local circulations and, possibly, local convective activity.

Simulation of the injection, dispersion, and scavenging of smoke emissions requires meso- and global-scale models not yet fully developed or coupled. Existing models treat processes in the upper half of the diagram and include multiscattering and absorption factors. Aerosol source functions, aerosol transport, and scavenging must also be added to present models, and simulation of convection and radiative processes must be improved. Major progress in this area requires considerable new research efforts.

The calculation of rapid transients in surface temperature is a crucially important aspect of large-scale circulation model studies of the nuclear war-climate problem. Many present models include only a zero heat capacity land surface and crude (if any) planetary boundary layer parameterizations. The importance of a better simulation of low-level cloud and radiation fog formation to the surface temperature transients must be studied using more detailed parameterizations than are presently incorporated. A combination of planetary boundary layer parameterization and improved surface physical processes (e.g., heat flow into the surface, effects of vegetation, local stability-dependent surface fluxes) must be included in any global model used

for nuclear war-climate research before we can have much confidence in the detailed time and space evolution of surface temperature. Surface and planetary boundary layer enhancements could be tested using the diurnal isolation cycles as a surrogate forcing.

Another type of modeling activity must also be performed. Although much of the debris from nuclear explosions and fires might be injected into the troposphere, substantial dust and possibly soot will be ejected into the stratosphere. Also, soot might rise into the stratosphere. Hence stratospheric dynamics may be as important as troposphere dynamics. The significance of dust and soot lifted into the stratosphere by nuclear explosions is that the stratospheric debris could have a long lifetime - on the order of years - and in certain scenarios large quantities of material may be placed into the stratosphere. The dust will have different optical properties than smoke and will be placed primarily in a different region of the atmosphere. Another class of global models, one devoted to stratospheric dynamics, will be needed to properly evaluate the spreading of the stratospheric debris. Significant dust loadings, or significant movement of soot into the stratosphere, could result in stratosphere clouds with enough optical depth to perturb the energy balance at the ground for long periods of time. Tropospheric models will not be adequate by themselves to properly consider this interaction. Hence an interplay between stratospheric circulation models and tropospheric ones will be needed.

In summary, the following specific areas where these models need to be improved include:

Vertical transport and convection parameterizations for heat, moisture, and momentum from the earth's surface through the

planetary boundary layer and troposphere under conditions possible after a nuclear exchange.

Surface parameterizations that permit accurate simulations of diurnal cycles and rapid surface temperature changes following a dust and smoke injection.

Hydrologic cycle representation that can accommodate changes in cloud and precipitation processes over a wide range of large-scale atmospheric states. Reformulation of parameterizations can provide assurance that the representations are capable of at least minimally handling dust and smoke interactions.

Incorporation and verification of aerosol processes in cloud, meso- and global-scale models that treat the injection, dispersion, and scavenging of smoke and the effects of smoke on radiative transfer and cloud physics.

Transport of aerosols from source regions, both horizontally and vertically (including transport on grid-scale and parameterized subgrid-scale). Simulations assuming unperturbed atmospheric dynamics have already been done and coupling of microphysical and dynamic models is now underway.

Precipitation scavenging and microphysics, including treatment of subgrid-scale scavenging processes, rain and ice interactions with particles, etc. in ways that remain accurate under a range of

possible perturbed atmospheric conditions. Cloud models are already being modified so that algorithms used in large-scale models can be calibrated. The modelling studies will make use of and provide guidance for other elements of the program.

Tropospheric chemistry and trace gases, particularly water vapor components and their infrared properties.

6. AGENCY RESPONSIBILITIES

Much of the work on evaluating the atmospheric effects of nuclear war has been done by small groups of government and nongovernment scientists. Those activities which have had federal sponsorship to date are summarized below by agency:

Department of Defense/Defense Nuclear Agency

Major responsibility for supporting nuclear effects research in the United States: fire research, modeling, and representative target data base development.

Department of Energy/Lawrence Livermore National Laboratory

Target data base development, source material, cloud-mesoscale dynamics, atmospheric modeling, firespread, microphysics, biological effects, and integrated analysis.

Department of Energy/Los Alamos National Laboratory

Mesoscale and global model development.

National Aeronautics and Space Administration/Ames

Source materials, radiative models, aerosol physics, stratospheric modeling, and analogue studies.

National Center for Atmospheric Research and University Scientists/

National Science Foundation

Global model development and sensitivity studies

Federal Emergency Management Agency

Supports research relevant to emergency management

National Oceanic and Atmospheric Administration/National Climate Program
Office

Coordination of interagency research plan.

The present research effort encompassed by the above in FY 1984 is about \$3.5 million funded by DOD and DOE. The DOD funds have supported internal research and also activities at Los Alamos, NCAR, and some universities. Related work at NASA and universities has resulted from other projects or studies such as atmospheric effects of dust storms on Mars and general modeling and climate studies.

REFERENCES

Aleksandrov V.V. and G.L. Stenchikov, 1983, "On the Modelling of the Climatic Consequences of the Nuclear War," The Proceeding on Applied Mathematics, (The Computing Centre of the Academy of Science of the USSR), 21 pp.

Alvarez L.W., W. Alvarez, F. Asaro, H.V. Michel, 1980, "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction," Science, 208, pp. 1095-1105.

Brinkman A.W. and J. McGregor, 1983, "Solar Radiation in Dense Saharan Aerosol in Northern Nigeria," Quart J. Roy. Meteor. Soc. 109, pp. 831-847.

Covey C., S.H. Schneider and S.L. Thompson, 1984, "Global Atmospheric Effects of Massive Smoke Injections from a Nuclear War: Results from General Circulation Model Simulations," Nature, 308, pp. 21-25.

Crutzen P.J. and J.W. Birks, 1982, "The Atmosphere After a Nuclear War: Twilight at Noon," Ambio II, no. 2-3, pp. 114-125.

Crutzen P., I. E. Galbally and C. Bruhl, 1984, "Atmospheric Effects from Post-Nuclear Fires," Climatic Change, Vol. 6, pp. 323-364.

Ehrlich A., 1984, "Nuclear Winter: A Forecast of the Climatic and Biological Effects of Nuclear War," Bull. Atomic Scientists, April, pp. 2-13.

Ehrlich P., 1984, "North America After the War," Natural History, April, pp. 5-8.

Ehrlich P.R., C. Sagan, D. Kennedy and W.O. Roberts, 1984, The Cold and the Dark: The World After Nuclear War, W.W. Norton, New York, 229 pp.

Ehrlich P., and 19 others, 1983, "Long-term Biological Consequences of Nuclear War," Science, 222, pp. 1293-1300.

Larson D.A. and R.D. Small, 1982, "Analysis of the Large Urban Fire Experiment, Part 1, Theory," Pacific Sierra Report 1210, Federal Emergency Management Agency, July.

MacCracken M.C., 1983, Nuclear War: Preliminary Estimates of the Climatic Effects of a Nuclear Exchange. UCRL-89770, Unpublished LLL.

Manabe S. and J.L. Hollaway, Jr., 1955, "Seasonal Variations of the Hydrologic Cycles as Simulated by a Global Model of the Atmosphere," Journal of Geophysical Research, 80, pp. 1617-1649.

National Academy of Sciences, 1968, Proceedings of the Symposium on Post-Attack Recovery from Nuclear War (National Academy of Sciences, Washington, D.C.)

National Academy of Sciences, 1975, Long-term World-wide Effects of Multiple Nuclear-Weapon Detonations (National Academy of Sciences, Washington, D.C.)

National Academy of Sciences, 1981, Current Mesoscale Meteorological Research in the United States (National Academy of Sciences, Washington, D.C.).

National Academy of Sciences, 1984, The Effects on the Atmosphere of a Major Nuclear Exchange (National Academy of Sciences, Washington, D.C.).

Penner, J.E., 1983, "Tropospheric Responses to a Nuclear Exchange," paper presented at the Third International Conference on Prevention of Nuclear War, Erice, Sicily, August.

Robock A., 1984, "Snow and Ice Feedbacks Prolong Effects of Nuclear Winter," Nature, 310, pp. 667-670.

Sagan C., 1983, "Nuclear War and Climatic Catastrophe: Some Policy Implications," Foreign Affairs, winter, pp. 257-292.

Singer S.F., 1984, "Is the Nuclear Winter Real? (Comments on paper by Covey, Schneider, and Thompson)," Nature, 310, 626.

Schneider S.H., and R. Londer, 1984, The Coevolution of Climate and Life, (Sierra Club Books, San Francisco), pp. 348-362.

Thompson S.L., V.V. Aleksandrov, G.L. Stenchikov, S.H. Schneider, C. Covey, and R.M. Chervin, 1984, "Global Climatic Consequences of Nuclear War: Simulation with Three-Dimensional Models," Ambio (in press).

Teller Edward, 1984, "The Widespread Aftereffects of Nuclear War," Nature, 310, 621-624.

Thompson S.L., S. H. Schneider and C. Covey, 1984, "Response to S. Fred Singer's Comments on Nuclear Winter", Nature, 310, 625-626.

Turco R.P., O.B. Toon, T.P. Ackerman, J.B. Pollack, and C. Sagan, 1983. "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," Science, 222, pp. 1283-1291.

APPENDIX A: National Research Plan Committees

COMMITTEE A: INTERAGENCY REVIEW COMMITTEE

John V. Byrne, Administrator, NOAA (Chairman)

Dr. Marvin C. Atkins
Deputy Director, Science
and Technology
Defense Nuclear Agency

Dr. Eugene W. Bierly
Director, Division of Atmospheric
Science
National Science Foundation

Mr. Danny Boggs
Deputy Secretary
Department of Energy

Mr. John M. Campbell, Jr.
Deputy Assistant Administrator
Office of Policy, Planning and
Evaluation
Environmental Protection Agency

Dr. Joseph O. Fletcher
Assistant Administrator for
Oceanic and Atmospheric
Research
NOAA

Dr. Alan D. Hecht
Director, National Climate Program
Office
NOAA

Dr. William Long
Director, Office of Environmental
Sciences
Department of State

Mr. Bernard A. Maguire
Associate Director
Federal Emergency Management
Agency

Dr. John J. Martin
Associate Administrator for
Aeronautics & Space Technology
NASA

Dr. Marvin Moss
Technical Director
Office of Naval Research

Mr. Louis Nosenzo
Deputy Assistant Director
for Strategic Programs
Arms Control & Disarmament
Agency

Dr. Charles B. Philpot
Director, Forest Fire and
Atmospheric Science Research
Department of Agriculture

Dr. Alvin W. Trivelpiece
Director, Office of Energy
Research
Department of Energy

Honorable Richard L. Wagner, Jr.
Assistant to the Secretary of
Defense (Atomic Energy)
Department of Defense

COMMITTEE B: DRAFTING COMMITTEE

A. D. Hecht, National Climate Program Office, Chairman

Captain Donald Alderson
OSD/USDRE/OATSD (AE)

Dr. Eugene W. Bierly
National Science Foundation

Dr. David W. Bensen
FEMA

Dr. John Birks
University of Colorado

Dr. Joseph Bishop
FEMA

Mr. Jack Campbell
Environmental Protection Agency

Dr. Robert D. Cess
State University of New York

Dr. Vernon Derr
Environmental Research Laboratory
NOAA

Mr. Peter Lunn
Defense Nuclear Agency

Dr. Michael MacCracken
Lawrence Livermore National Laboratory

Dr. Robert Malone
Los Alamos Laboratory

Dr. Michael May
Lawrence Livermore National
Laboratory

Dr. Harold D. Orville
South Dakota School of Mines
and Technology

Dr. James Pollack
Ames Research Center, NASA

Dr. Lawrence Radke
University of Washington

Dr. Starley Thompson
National Center for Atmospheric
Research

Dr. Brian Toon
Ames Research Center, NASA

Dr. Darold Ward
U.S. Forest Service

Dr. Martin Yerg
National Climate Program Office

APPENDIX B: Ranges of Uncertainties in "Nuclear Winter" Calculations
(prepared by Michael C. MacCracken, Lawrence Livermore National Laboratory)

TABLE B-1: HOW MUCH SMOKE IS GENERATED?

Factors	Oft-Used Value	Range	Depends on:
Number of explosions combustible targets	6,000	Few to several thousand or more	Scenario
Fraction of unburned,	20%	Few to 100%	Targeting strategy, overlap, likelihood of ignition
Combustible fuel density (g/cm ²)	~3 in cities 0.5 in forests	0.1 to 10 s	Target type, for forests depends on time of year
Area per fire (km ²)	200	10-1000	Yield, target, weather, likelihood of spreading, burst height, topography, fluence for ignition
Lofted aerosol fraction <1.0 μm	~3 x 10 ⁻²	10 ⁻³ - few 10 ⁻²	Nature of fuel, nature of fire, fraction of fuel burned
Total aerosol mass (g)	2 x 10 ¹⁴ = 200 Tg	10-1000 Tg	Present U.S. forest fire injection is about 10 Tg/yr, global atm soot loading < 1 Tg

B-1

APPENDIX B

TABLE B-2: HOW HIGH DOES SMOKE PLUME GO? HOW MUCH IS INJECTED?

Factors	Oft-Used Value	Range	Depends on:
Plume height	Up to 10 km	Few to 20 km	Type of fire (urban, forest, etc.), fire size and intensity, atmospheric temperature structure, winds, etc.
Fraction lofted to stratosphere via firestorm	5%	0-20%	Fire intensity, atmospheric temperature structure, winds, etc.
Particle transformation via:			
Chemistry	Neglected	Changes composition	Particle size, composition, number density, atmospheric conditions, relative humidity, clean air entrainment, temperature, etc.
Coagulation	Slow	Could be fast at early time	
Cloud/particle interaction	Neglected	Changes size distribution and optical properties of cloud	
Rainout, scavenging	25%	Few to > 50%	

TABLE B-3: WHAT ARE THE SOLAR AND INFRARED RADIATIVE EFFECTS?

Factors	Oft-Used Value	Range	Depends on:
Smoke reduction of Northern Hemisphere solar radiation (light) reaching surface (optical depth = 3)	> 90%	0 in clear areas, up to 99+% under thick smoke clouds	Composition, amount, particle size distribution, particle shape
Size distribution	Peaks ~0.1 μm , log-normal	Initially not log-normal, size changes in time	Formation process, coagulation and scavenging processes
Single scatter albedo of smoke particles	0.5	0.5-0.8	Particle composition, shape, etc.
Composition	Soot coated by hydrocarbons	Wide range depending on mixture of fuels	Formation processes, chemical evolution
Shape	Spherical	May be strongly nonspherical (aspect ratio of 10 is possible)	Formation and coagulation processes. Shape probably not important except for large aggregates
Smoke effect on IR radiation	Negligible	Could be large effect for thick smoke cloud	Size distribution, shape, and composition of smoke particles

TABLE B-4: THEN WHAT HAPPENS?

Factors	Oft-Used Value	Range	Depends on:
Mesoscale transformation and scavenging	Ignored	Could be very important	Weather conditions, dynamic perturbations
Mesoscale spreading	Unperturbed spread in vertical, very rapid speed in horizontal direction	Horizontal and vertical spreading rate could be slowed or accelerated dramatically, depending on dynamic interactions.	Weather, self-induced heating and spreading of smoke, creation of patchiness by storms
Hemispheric transformation and scavenging	Unperturbed	Could be accelerated or slowed	Perturbation to mesoscale (e.g., ocean-land contrast) and global dynamics and atmospheric vertical structure (convection)
Hemispheric spreading	Instantaneous	Likely slow, especially to Southern Hemisphere, unless self-induced	Season, windspeed, perturbation to atmospheric circulation pattern
Temperature change	Severe and rapid cooling of land	Small to severe	Smoke patchiness, ocean buffering, perturbed dynamics, time of year, cloudiness, altitude of injection, optical properties of smoke, etc.

TABLE B-5: WHAT ARE THE ECOLOGICALLY IMPORTANT CHANGES?

Factors	Oft-Used Value	Range	Depends on:
Reduction in available sunlight	90%	Few-100%	Spreading rate of aerosol, patchiness, smoke properties
Mid-latitude temperature change on land	-30 to -40:C	Near zero to -30:C or more, will be larger in summer than winter	Season, latitude, extent of ocean buffering, topography/geography, vertical and horizontal spreading rate of aerosol, climatic feedbacks
Tropical and southern hemisphere temperature change on land	-20 to -40:C	Near zero to -20:C	Rate and degree of spreading of smoke, scavenging rate of smoke, ocean buffering of temperature change
Duration of temperature change	Few months, with immediate onset	Few days to year, with possibly rapid onset under some conditions	Lifetime of soot in atmosphere, soot distribution and rate of spread
Precipitation change	Decrease	Increase or decrease	Location (coast vs. inland), latitude, change in atmospheric stability, possible early scavenging in convection induced by smoke plume
Surface winds and storminess	Increase	Increase or decrease	Dynamic response to temperature contrasts and perturbations

Mike Hawley

DRAFT

SECRETARY OF DEFENSE

CASPAR W. WEINBERGER



**THE POTENTIAL EFFECTS OF NUCLEAR WAR
ON THE CLIMATE**

A REPORT TO THE UNITED STATES CONGRESS

27 FEB 1985

TABLE OF CONTENTS

SUBJECT	PAGE
Preface	ii
1. Technical Issues	1
The Climatic Response Phenomena	2
Historical Perspective	2
Uncertainties	3
National Academy of Science Report, 1984	6
The Ongoing DoD and DoE Research Effort	7
Inter-Agency Research Program	8
2. Summary Observations on the Current Appreciation of the Technical Issues	9
3. Policy Issues	10
Deterrence	10
Strategic Modernization Program	12
Arms Reductions	12
The Strategic Defense Initiative	13
Civil Defense	14
Possible Further Initiatives	15
4. Soviet Perceptions of Climate Effects	16

PREFACE

This report to the Congress on the potential climatic effects of nuclear war has been prepared to satisfy provisions contained in Section 1107 of the Department of Defense Authorization Act, 1985, as follows:

"Sec. 1107 (a) The Secretary of Defense shall participate in any comprehensive study of the atmospheric, climatic, environmental, and biological consequences of nuclear war and the implications that such consequences have for the nuclear weapons strategy and policy, the arms control policy, and the civil defense policy of the United States.

(b) Not later than March 1, 1985, the Secretary of Defense shall submit to the Committees on Armed Services of the Senate and House of Representatives an unclassified report suitable for release to the public, together with classified addenda (if required), concerning the subject described in subsection (a). The Secretary shall include in such report the following:

(1) A detailed review and assessment of the current scientific studies and findings on the atmospheric, climatic, environmental, and biological consequences of nuclear explosions and nuclear exchanges.

(2) A thorough evaluation of the implications that such studies and findings have on (A) the nuclear weapons policy of the United States, especially with regard to strategy, targeting, planning, command, control, procurement, and deployment, (B) the nuclear arms control policy of the United States, and (C) the civil defense policy of the United States.

(3) A discussion of the manner in which the results of such evaluation of policy implications will be incorporated into the nuclear weapons, arms control, and civil defense policies of the United States.

(4) An analysis of the extent to which current scientific findings on the consequences of nuclear explosions are being studied, disseminated, and used in the Soviet Union."

This report deals explicitly only with the atmospheric and climatic effects of nuclear war, and does not deal with other effects which could have environmental or biological consequences. This is for several reasons: the original motivation for the request stemmed, we believe, from recent analyses pointing to possible severe climatic effects--so called "nuclear winter." Other effects, both the horrible immediate devastation, and long-term effects such as widespread fallout or ionospheric chemistry perturbations, have been dealt with previously, and the newly postulated climatic effects, at the possible extremes indicated by some analyses, would either be dwarfed or would probably be surpassed by these better understood effects.

On past occasions when other more immediate kinds of global effects have been under active assessment--and there have been several such episodes over the years--it took some time for their magnitude and implications to be assessed. This will also be true for the current issue of climatic effects. And in each previous case, the conclusion was drawn that, even were the effect to have been very widespread and very severe, the most basic elements of our policy remain sound: nuclear war must and can be prevented, and to accomplish this imperative, the United States must maintain a strong deterrent capability. This requirement remains true today. Moreover, there are two further considerations which bear on the issue of global effects of nuclear war and our deterrent policy. First, we believe the prospects are promising for significant reductions in offensive weapons. Second, strategic defense may offer a path to reduce the threat of nuclear devastation.

The report commences with a review of the current understanding of the technical issues, and then describes the implications of that understanding, concluding with a description of Soviet activities concerning the analysis of the phenomena.

PREFACE

This report to the Congress on the potential atmospheric and climatic effects of nuclear war has been prepared to satisfy provisions contained in Section 1107 of the Department of Defense Authorization Act, 1985, as follows:

"Sec. 1107 (a) The Secretary of Defense shall participate in any comprehensive study of the atmospheric, climatic, environmental, and biological consequences of nuclear war and the implications that such consequences have for the nuclear weapons strategy and policy, the arms control policy, and the civil defense policy of the United States.

(b) Not later than March 1, 1985, the Secretary of Defense shall submit to the Committees on Armed Services of the Senate and House of Representatives an unclassified report suitable for release to the public, together with classified addenda (if required), concerning the subject described in subsection (a). The Secretary shall include in such report the following:

(1) A detailed review and assessment of the current scientific studies and findings on the atmospheric, climatic, environmental, and biological consequences of nuclear explosions and nuclear exchanges.

(2) A thorough evaluation of the implications that such studies and findings have on (A) the nuclear weapons policy of the United States, especially with regard to strategy, targeting, planning, command, control, procurement, and deployment, (B) the nuclear arms control policy of the United States, and (C) the civil defense policy of the United States.

(3) A discussion of the manner in which the results of such evaluation of policy implications will be incorporated into the nuclear weapons, arms control, and civil defense policies of the United States.

(4) An analysis of the extent to which current scientific findings on the consequences of nuclear explosions are being studied, disseminated, and used in the Soviet Union."

This report deals explicitly only with the atmospheric and climatic effects of nuclear war, and does not deal with other effects which could have environmental or biological consequences. This is for several reasons: the original motivation for the request stemmed, we believe, from recent analyses pointing to possible severe climatic effects--so called "nuclear winter." Other possible effects, such as widespread fallout or ionospheric chemistry perturbations, have been dealt with previously, and the newly postulated climatic effects, at the possible extremes indicated by some analyses, would probably dominate these older effects.

On past occasions when these other kinds of global effects have been under active assessment--and there have been several such episodes over the years--it took some time for their magnitude and implications to be assessed. This will also be true for the current issue of climatic effects. And in each previous case, the conclusion was drawn that, even were the effect to have been very widespread and very severe, the most basic elements of our policy remain sound: nuclear war must and can be prevented and to accomplish this imperative, the United States must maintain a strong deterrent capability. This requirement remains true today, but today there are two additional considerations. First, we believe the prospects are promising for significant reductions in offensive weapons. Second, strategic defense offers a path to reduce the threat of nuclear devastation.

The report commences with a review of the current understanding of the technical issues, and then describes the implications of that understanding, concluding with a description of Soviet perceptions of the phenomena.

THE POTENTIAL EFFECTS OF NUCLEAR WAR ON THE CLIMATE

A REPORT TO THE UNITED STATES CONGRESS

1. Technical Issues

The Climatic Response Phenomena: The basic phenomena that could lead to climatic response may be described very simply. In a nuclear attack, fires would be started in and around many of the target areas either as a direct result of the thermal radiation from the fireball or indirectly from blast and shock damage. Examples of the latter would be fires started by sparks from electrical short circuits, broken gas lines and ruptured fuel storage tanks. Such fires could be numerous and could spread throughout the area of destruction and in some cases beyond, depending on the amount and type of fuel available and local meteorological conditions. These fires might generate large quantities of smoke which would be carried into the atmosphere to varying heights, depending on the meteorological conditions and the intensity of the fire.

In addition to smoke, nuclear explosions on or very near the earth's surface can produce dust that would be carried up with the rising fireball. As in the case of volcanic eruptions such as Mt. Saint Helens, a part of the dust would probably be in the form of very small particles that do not readily settle out under gravity and thus can remain suspended in the atmosphere for long periods of time. If the yield of the nuclear explosion were large enough to carry some of the dust into the stratosphere where moisture and precipitation are not present to wash it out, it could remain for months.

Thus, smoke and dust could reach the upper atmosphere as a result of a nuclear attack. Initially, they could be injected into the atmosphere from many separate points and to varying heights. At this point, several processes would begin to occur simultaneously. Over time, circulation within the atmosphere would begin to spread the smoke and dust over wider and wider areas. The circulation of the atmosphere would itself be perturbed by absorption of solar energy by the dust and smoke clouds, so it could be rather different from normal atmospheric circulation. There may also be processes that could transport the smoke and dust from the troposphere into the stratosphere. At the same time, the normal processes that cleanse pollution from the lower-and middle-levels of the atmosphere would be at work. The most obvious of these is precipitation or washout, but there are several other mechanisms also at work. While this would be going on, the physical and chemical characteristics of the smoke and dust could change so that, even though they are still suspended in the atmosphere, their ability to absorb or scatter sunlight would be altered.

Depending upon how the atmospheric smoke and dust generated by nuclear war are ultimately characterized, the suspended particulate matter could act much like a cloud, absorbing and scattering sunlight at high altitude and reducing the amount of solar energy reaching the surface of the earth. How much and how fast the surface of the earth might cool as a result would depend on many of the yet undetermined details of the process, but if there is sufficient absorption of sunlight over a large enough area, the temperature change could be significant. If the smoke and dust clouds remained concentrated over a relatively small part of the earth's surface, they might produce sharp drops in the local temperature under them; but the effect on the hemispheric (or global) temperature would be slight since most areas would be substantially unaffected.

However, the natural tendency of the atmosphere, disturbed or not, would be to disperse the smoke and dust over wider and wider areas with time. One to several weeks would probably be required for widespread dispersal over a region thousands of kilometers wide. Naturally, a thinning process would occur as the particulate matter spread. At the end of this dispersal period, some amount of smoke and dust would remain, whose ability to attenuate and/or absorb sunlight would depend on its physical and chemical state at the time. By this time, hemispheric wide effects might occur. Temperatures generally would drop and the normal atmospheric circulation patterns (and normal weather patterns) could change. How long temperatures would continue to drop, how low they would fall, and how rapidly they would recover, all depend on many variables and the competition between a host of exacerbating and mitigating processes.

Uncertainties also pervade the question of the possible spread of such effects to the southern hemisphere. Normally the atmospheres of the northern and southern hemispheres do not exchange very much air across the equator. Thus, the two hemispheres are normally thought of as being relatively isolated from one another. However, for high enough loading of the atmosphere of the northern hemisphere with smoke and dust, the normal atmospheric circulation patterns might be altered and mechanisms have been suggested that would cause smoke and dust from the northern hemisphere to be transported into the southern hemisphere.

There is fairly general agreement, at the present time, that for major nuclear attacks the phenomena could proceed about as we have described, although there is also realization that important processes might occur that we have not yet recognized, and these could work to make climatic alteration either more or less serious. However, the most important thing that must be realized is that even though we may have a roughly correct qualitative picture, what we do not have, as will be discussed later, is the ability to predict the corresponding climatic effect quantitatively; significant uncertainties exist about the magnitude, and persistence of these effects. At this time, for a postulated nuclear attack and for a specific point on the earth, we cannot predict quantitatively the materials which may be injected into the atmosphere, or how they will react there. Consequently, for any major nuclear war, some decrease in temperature may occur over at least the northern mid-latitudes. But what this change will be, how long it will last, what its spatial distribution will be, and, of much more importance, whether it will lead to effects of equal or more significance than the horrific destruction associated with the short-term effects of a nuclear war, and the other long-term effects such as radioactivity, currently is beyond our ability to predict, even in gross terms.

Historical Perspective: New interest in the long-term effects on the atmosphere of nuclear explosions was raised in 1980 when scientists proposed that a massive cloud of dust caused by a meteor impact could have led to the extinction of more than half of all the species on earth (Alvarez et al., 1980). The concept of meteor-impact dust affecting the global climate led to discussions at the National Academy of Sciences (NAS) in 1981. In April 1982, an ad hoc panel met at the Academy to assess the technical aspects of nuclear dust effects. At the meeting, the newly-discovered problem of smoke (see below) was brought up. The potential importance of both smoke and dust in the post-nuclear environment was recognized by the panel, who wrote a summary letter

recommending that the Academy proceed with an in-depth investigation. In 1983, the Defense Nuclear Agency agreed to sponsor this investigation, on behalf of the Department of Defense. The results were published in the National Research Council report "The Effects on the Atmosphere of a Major Nuclear Exchange," released in December 1984.

Appreciation of smoke as a major factor resulted from the work of Crutzen and Birks. In 1981, Ambio, the Journal of Swedish Academy of Sciences, arranged a special issue on the physical and biological consequences of nuclear war. Crutzen was commissioned to write an article on possible stratospheric ozone depletions. He and Birks extended their analysis to include nitrogen oxides (NO_x) and hydrocarbon air pollutants generated by fires. Crudely arguing from historical forest fire data, they speculated that one million square kilometers of forests might burn in a nuclear war. They estimated very large quantities of smoke would be produced as a result. Subsequent evaluations based upon hypothetical exchanges have yielded much smaller burned areas and smoke production. Nevertheless, their work provided insight and impetus for subsequent studies.

The first rough quantitative estimates of the potential magnitude of the effects of nuclear war on the atmosphere were contained in a paper published in Science in December 1983⁽¹⁾ generally referred to as TTAPS, an acronym derived from the first letter of the names of the five authors. This study estimated conditions of near-darkness and sub-freezing land temperatures, especially in continental interiors, for up to several months after a nuclear attack--almost independent of the level or type of nuclear exchange scenario used. TTAPS suggested that the combination of all of the long-term physical, chemical, and radiobiological effects of nuclear explosions could, on a global scale, prove to be as serious or more serious than the immediate consequences of the nuclear blasts, although no specific damage or casualty assessments were carried out for either the immediate effects or the effects of the postulated climatic changes.

While the Crutzen and Birks studies stirred some interest in scientific circles, the TTAPS study, and its widespread dissemination in various popular media, brought the problem to wide public attention. Because of its widespread dissemination, it is important to review this work in detail, and, because the salient feature of our current understanding is the large uncertainties, we will begin by discussing the nature of the uncertainties, using the TTAPS study as a vehicle for the discussion.

Uncertainties: The model used in the TTAPS study was actually a series of calculations that started with assumed nuclear exchange scenarios and ended with quantitative estimate of an average hemispheric temperature decrease. Since these phenomena are exceedingly complex and outside the bounds of our normal experience, one is forced to employ many estimates, approximations, and educated guesses to arrive at quantitative results. To appreciate the significance of the predictions derived from the TTAPS model, it is necessary to understand some of its features and limitations.

(1) Turco, R. P. et al.; Nuclear Winter: Global Consequences of Multiple Nuclear Explosions; Science, 23 December 1983, VOL 222, Number 4630.

Looked at most broadly, there are three phases to the modeling problem: the initial production of smoke and dust; its injection, transport, and removal within the atmosphere; and the consequent climatic effects.

In the TTAPS model, the amount of smoke initially produced for any given scenario was probably the most uncertain parameter. This is because a large number of poorly-known variables were combined to determine the amount of smoke that could be produced from any single nuclear explosion. In actuality, the same yield weapon could produce vastly different amounts of smoke over different target areas and under different meteorological conditions. Some of the factors that must be considered--although not taken into account in the TTAPS study--include: the thermal energy required for ignition of the various fuels associated with a particular target area, the sustainability of such a fire, the atmospheric transmission and the terrain features which will determine the area receiving sufficient thermal energy from the fireball to cause ignition, the type and quantity of combustible material potentially available for burning, the fraction that actually burns, and finally, the amount of smoke produced per unit mass of fuel burned. Every target is unique with respect to this set of characteristics, and a given target may change greatly depending on local weather, season, or even time of day.

The TTAPS study did not attempt to analyze the individual targets or areas used for their various scenarios; rather, it made estimates of average or plausible values for all the parameters needed to satisfy the model. This procedure is not unreasonable and is consistent with the level of detail in the analysis, but the potential for error in estimating these averages is clearly quite large. In one case, a more detailed assessment of smoke production has recently been completed as a result of the ongoing DoD research in this area. Bush and Small⁽²⁾ have made an analysis of smoke produced as a result of hypothetical non-urban wildfires which one can directly compare with the corresponding modeling assumption used in this TTAPS scenario. Bush and Small studied 3,500 uniquely located, but hypothetical targets, characterizing each according to monthly average weather, ignition area, fuel loading, fire spread, and smoke production. The results showed a significantly smaller smoke production--by a factor of over 30 in July to almost 300 in January--than comparable TTAPS results. An effort is underway to resolve this great difference. It is cited here to illustrate the very large current uncertainties in only one of several critically important parameters.

In the TTAPS analysis, smoke was more important than dust in many cases, and as a result popular interest has tended to focus on fires rather than dust. This may or may not be the correct view. If smoke is systematically overestimated, especially in scenarios that should emphasize dust production over smoke (such as attacks on silos using surface bursts), analytic results will be skewed. Additionally, uncertainties associated with the lofting of dust are large because of limited data from atmospheric nuclear tests carried out prior to 1963. This is because most tests were not relevant to the question of

(2) Small, R.D., Bush, B. W.; Smoke Production from Multiple Nuclear Explosions in Wildlands; Pacific Science Research Corporation, in publication.

surface or near-surface bursts over continental geology, or the relevant measurements were not made. The range of uncertainty for total injected mass of submicron size dust, that which is of greatest importance, is roughly a factor of ten, based on our current knowledge.

After generation of smoke and dust is estimated, a model must then portray its injection into the atmosphere, the removal processes, and the transport both horizontally and vertically. The TTAPS model did not directly address these processes since it is a one-dimensional model of the atmosphere. By one-dimensional, one means that the variation of atmospheric properties and processes are treated in only the vertical direction. There is no latitudinal or longitudinal variation as in the real world. A one-dimensional model can only deal with horizontally averaged properties of the entire hemisphere. Of great significance, the land, the oceans, and the coastal interface regions cannot be treated. This is a critical deficiency because the ocean, which covers almost three-fourths of the earth's surface, has an enormous heat capacity compared to the land and will act to moderate temperature changes, especially near coastlines and large lakes. The TTAPS authors did acknowledge this limitation and pointed out that these effects would lessen their predicted temperature drops.

Because there is no horizontal (latitude and longitude) dependence in a one-dimensional model, the extent to which smoke and dust would be injected into the atmosphere over time were not estimated in a realistic way. Instead, the total smoke and dust estimated for a given scenario was placed uniformly over the hemisphere at the start of their calculation. The most certain effect of all this is that the hemisphere average temperature drops very rapidly--much faster than it would in a more realistic three-dimensional model using the same input variables.

The one-dimensional model has other shortfalls. Recovery from the minimum temperatures would largely be accomplished through the gradual removal of smoke and dust, and it was assumed that this removal rate would be the same in the perturbed atmosphere as it is in the normal atmosphere. Even in the normal atmosphere, removal of pollutants is a poorly understood process. Most pollution removal depends on atmospheric circulation and precipitation, but in an atmosphere with a very heavy burden of smoke and dust, the circulation and weather processes may be greatly altered. Some potential alterations could lead to much slower removal than normal, others to more rapid removal. Currently we have little insight into this uncertainty.

This discussion of the deficiencies of the one-dimensional TTAPS model is not meant as a criticism. A one-dimensional model is a valuable research tool and can provide some preliminary insights into the physical processes at work. The three-dimensional models needed to treat the problem more realistically are exceedingly complex and will require very large computational resources. The DoD and Department of Energy, in conjunction with the National Center for Atmospheric Research (NCAR) and other agencies, are pursuing the development of three-dimensional models to treat the atmospheric effects problem. Our work is progressing, and the first results of this effort are now beginning to appear. Though very preliminary and not a complete modeling of any specific scenario, they suggest that:

- o Substantial scavenging of smoke injected into the lower atmosphere from the continents of the Northern Hemisphere may occur as the smoke is being more widely dispersed over the hemisphere.
- o Lofting of smoke through solar heating could act to increase the lifetime of the remaining smoke and may reduce the sensitivity to height of injection.
- o For very large smoke injections, global-scale spreading and cooling are more likely in summer than in winter.

Despite good initial progress, many basic problems remain to be solved in the areas of smoke and dust injection, transport, and removal. In order to make the results produced by these models more accurate, we must improve our understanding of the basic phenomena occurring at the micro, meso, and global scale.

One final problem should be mentioned. Dust and smoke have the potential to effect the climate only because of their ability to absorb and scatter sunlight. The absorption and scattering coefficients of the various forms of smoke, dust, and other potential nuclear-produced pollutants must be known before any realistic predictions can be expected. Here again there is a large uncertainty, and what we do know about pollutants in the normal atmosphere may not be correct for the conditions in a significantly altered atmosphere.

National Academy of Sciences Report, 1984: Following their preliminary review of the possible effects of nuclear war-induced smoke and dust in April 1982, the NAS came to an agreement with DNA, acting on behalf of the DoD, to support a full-fledged study. The first committee meeting occurred at the NAS in March 1983. The NAS committee adopted the one-dimensional TTAPS analysis as a starting point for their investigation. During the course of the study, virtually all of the work going on pertinent to this phenomenon was reviewed.

The result of this effort was the NAS report, "The Effects on the Atmosphere of a Major Nuclear Exchange," released on December 11, 1984.

The conclusion of the report states that:

"... a major nuclear exchange would insert significant amounts of smoke, fine dust, and undesirable species into the atmosphere. These depositions could result in dramatic perturbations of the atmosphere lasting over a period of at least a few weeks. Estimation of the amounts, the vertical distributions, and the subsequent fates of these materials involves large uncertainties. Furthermore, accurate detailed accounts of the response of the atmosphere, the redistribution and removal of the depositions, and the duration of a greatly degraded environment lie beyond the present state of knowledge.

"Nevertheless, the committee finds that, unless one or more of the effects lie near the less severe end of their uncertainty ranges, or unless some mitigating effect has been overlooked, there is a clear possibility that great portions of the land areas of the northern temperate zone (and,

perhaps, a large segment of the planet) could be severely affected. Possible impacts include major temperature reductions (particularly for an exchange that occurs in the summer) lasting for weeks, with subnormal temperatures persisting for months. The impact of these temperature reductions and associated meteorological changes on the surviving population, and on the biosphere that supports the survivors, could be severe, and deserves careful independent study.

"... all calculations of the atmospheric effects of a major nuclear war require quantitative assumptions about uncertain physical parameters. In many areas, wide ranges of values are scientifically credible, and the overall results depend materially on the values chosen. Some of these uncertainties may be reduced by further empirical or theoretical research, but others will be difficult to reduce. The larger uncertainties include the following: (a) the quantity and absorption properties of the smoke produced in very large fires; (b) the initial distribution in altitude of smoke produced in large fires; (c) the mechanism and rate of early scavenging of smoke from fire plumes, and aging of the smoke in the first few days; (d) the induced rate of vertical and horizontal transport of smoke and dust in the upper troposphere and atmosphere; (e) the resulting perturbations in atmospheric processes such as cloud formation, precipitation, storminess, and wind patterns, and (f) the adequacy of current and projected atmospheric response models to reliably predict changes that are caused by a massive, high altitude, and irregularly distributed injection of particulate matter. The atmospheric effects of a nuclear exchange depend on all of the foregoing physical processes, (a) through (e)., and their ultimate calculation is further subject to the uncertainties inherent in (f)."

The Interagency Research Program (IRP): The genesis of this program stems from ongoing DoD and DoE research efforts. In 1983, both the DoD and the DoE started research on the atmospheric response phenomena. In addition to sponsoring the NAS study just discussed, the DoD portion of the program addressed a broad range of issues associated with the long-term global climatic effects of nuclear exchange. This program (\$400K in FY83, \$1100K in FY84, \$1500K in FY85, \$2500K in FY86 and continuing at appropriate levels into the future) supports research on several fronts--at numerous government laboratories, universities, and contractors. Included among the government laboratories are National Bureau of Standards (NBS), National Center for Atmospheric Research (NCAR), the National Aeronautical and Space Administration (NASA) laboratories at Ames and Langley, and the DoE laboratories at Los Alamos and Livermore.

The DoD portion of the IRP emphasizes research in (1) the smoke and dust source terms, including the definition of total ignition area, fuel loading and fire spreading, and particulate production, (2) large-scale fire characteristics, particulate lofting, scavenging, coagulation, rain-out, and atmospheric injection, (3) chemistry, including the chemical kinetics of fires and fireballs, the chemical consequences of mesoscale and global processes, and radiative properties (optical and infrared absorption, emission, and scattering), and (4) climatic effects, including the improvement of mesoscale and global climate models to incorporate better particulate source functions; horizontal advection processes; vertical mixing; solar radiation; particulate

scavenging; inhomogeneities; particulate, radiative, and circulation feedbacks; seasonal differences; and particulate spreading.

The effort supported by the DoE is fully coordinated with that of the DoD and is currently funded at roughly \$2M per year. The LLNL program is broad-based and includes modeling of urban fire ignition, plume dynamics, climate effects, radioactive fallout, and biological impacts. The LANL program focuses on developing comprehensive models for global-scale climate simulations. It is coordinated with complementary efforts at NCAR and NASA Ames. The IRP came into being with approval of the draft Research Plan for Assessing the Climatic Effects of Nuclear War prepared by a committee of university and government scientists. The plan was initiated by Presidential Science Advisor, Dr. George Keyworth, with the National Climate Program Office of NOAA heading the preparation effort. This program augments and coordinates the research activities currently underway in the DoD and the DoE with other government agencies. The program focuses particularly on the problems of fire dynamics, smoke production and properties, and mesoscale processes. The proposed additional research includes increases in theoretical studies, laboratory experiments, field experiments, modeling studies, and research on historical and contemporary analogues of relevant atmospheric phenomena.

The IRP recognizes the need for expertise from a number of experts inside and outside of the Federal Government--many are already at work on the problem. Participating government agencies would include the Department of Defense (DNA), Department of Energy (LLNL, LANL), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), National Bureau of Standards, National Aeronautics and Space Administration (NASA), Federal Emergency Management Agency (FEMA), and the U.S. Forest Service.

The major goals of the IRP are to accelerate the research to reduce the numerous uncertainties in smoke sources and to improve modeling of atmospheric effects. Although it is recognized that not all of the uncertainties could be reduced to uniform or perhaps even to acceptable levels, it is clearly possible to improve our knowledge of the climatic consequences of nuclear exchanges.

2. Summary Observations on the Current Appreciation of the Technical Issues

The Department of Defense recognizes the importance of improving our understanding of the technical underpinnings of the hypothesis which asserts, in its most rudimentary form, that if sufficient material, smoke, and dust are created by nuclear explosions, lofted to sufficient altitude, and were to remain at altitude for protracted periods, deleterious effects would occur with regard to the earth's climate.

We have very little confidence in the near-term ability to predict this phenomenon quantitatively, either in terms of the amount of sunlight obscured and the related temperature changes, the period of time such consequences may persist, or of the levels of nuclear attacks which might initiate such consequences. We do not know whether the long-term consequences of a nuclear war--of whatever magnitude--would be the often postulated months of subfreezing temperatures, or a considerably less severely perturbed atmosphere. Even with widely ranging and unpredictable weather, the destructiveness for human survival of the less severe climatic effects might be of a scale similar to the other horrors associated with nuclear war. As the Defense Science Board Task Force on Atmospheric Obscuration found in their interim report:

"The uncertainties here range, in our view, all the way between the two extremes, with the possibility that there are no long-term climatic effects no more excluded by what we know now than are the scenarios that predict months of sub-freezing temperatures."

These observations are consistent with the findings in the NAS report, summarized earlier in this report. We believe the NAS report has been especially useful in highlighting the assumptions and the considerable uncertainty that dominate the calculations of atmospheric response to nuclear war. While other authors have mentioned these uncertainties, the NAS report has gone to considerable length to place them in a context which improves understanding of their impact.

We agree that considerable additional research needs to be done to understand better the effects of nuclear war on the atmosphere, and we support the IRP as a means of advancing that objective. However, we do not expect that reliable results will be rapidly forthcoming. As a consequence, we are faced with a high degree of uncertainty, which will persist for some time.

Finally, in view of the present and prospective uncertainties in these climatic predictions, we do not believe that it is possible at this time to draw competent conclusions on their biological consequences, beyond a general observation similar to that in the NAS report: if the climatic effect is severe, the impact on the surviving population and on the biosphere could be correspondingly severe.

3. Policy Implications

The issues raised by the possibility of effects of nuclear war on the atmosphere and climate only strengthen the basic imperative of U.S. national security policy--that nuclear war must be prevented. For over 40 years, we have achieved this objective through deterrence and in the past 20 years we have sought to support it through arms control. Now, through the Strategic Defense Initiative, we are seeking a third path to reduce the threat of nuclear devastation.

In the remainder of this report, we will first discuss these three principal elements of our posture--deterrence, arms control, and the Strategic Defense Initiative--briefly describing each one and discussing how it relates to the issue of possible severe climatic effects. We conclude, in this regard, that these three elements, and the initiatives we are taking for each of them, remain fundamentally sound. We then explore the possibility of additional initiatives explicitly designed to mitigate climatic effects, concluding that, while some may be possible, the state of our technical understanding of these phenomena is not yet mature enough to have allowed development of specific initiatives. Finally, we review Soviet perceptions of climatic effects and their implications. We observe that Soviet perceptions are very important--indeed, that differences between their perceptions and ours would be particularly important. We conclude, however, that they have done little original work on the subject and show no evidence of regarding the whole matter as anything more than an opportunity for propaganda.

Deterrence: The evolution of U.S. strategic doctrine from the late-1940s to date is well documented. Throughout the past four decades, our policy has had to convince the Soviet leadership of the futility of aggression by ensuring that we possessed a deterrent which was sufficiently credible and capable to respond to any potential attack. Two years ago next month, the President's Commission on Strategic Forces, under the able leadership of Brent Scowcroft, confirmed anew that effective deterrence requires:

- Holding at risk those military, political and economic assets which the Soviet leadership have given every indications by their actions they value most and which constitute their tools of power and control;
- Creating a stable strategic balance by eliminating unilateral Soviet advantages and evolving to increasingly survivable deterrent forces; and
- Maintaining a modern, effective strategic Triad by strengthening each of its legs and emphasizing secure and survivable command, control and communications.

These three principles are reflected in our strategic modernization program discussed below. Consistent with meeting our essential targeting requirements which derive from these three overarching deterrence principles, we also observe other policy considerations, three of which warrant special mention because they may serve to reduce concerns about climatic effects. They are a reduction of the number of weapons and total yield, rejection of targeting urban population

as a way of achieving deterrence, and escalation control. Reducing unwanted damage must be an important feature of our policy, not only because of a categorical desire to limit damage that is not necessary, but also because it adds to the credibility of our response if attacked and thus strengthens deterrence. Over the past 20 years or so, this policy and other considerations have resulted in development of systems which are more discriminating. This, in turn, has led to reductions of some 30% of the total number of weapons and nearly a factor of four reduction in the total yield of our stockpile. This direction continues today, and the prospects for extremely accurate and highly effective non-nuclear systems are encouraging.

Some analyses of climatic effects of nuclear war have assumed targeting of cities. If this were regarded as an inevitable result of nuclear attack, or as U.S. policy, it would completely distort analysis of climatic effects, but more importantly, it would perpetuate a basic misperception of the nature of deterrence. We believe that threatening civilian populations is neither a prudent nor a moral means of achieving deterrence, nor in light of Soviet views, is it effective. Attacks designed to strike population would, by virtue of deliberately targeting heavily built up urban centers, necessarily have a high probability of starting major fires, and consequently, of creating large amounts of smoke. But our strategy consciously does not target population and, in fact, has provisions for reducing civilian casualties. As part of our modernization program, we are retiring older deterrent systems (e.g., the Titan missile) which would might created a greater risk of climatic effect than their replacement.

A third element of our implementation of deterrence policy which bears on a mitigation of possible climatic effects is escalation control. It is our position that, however an adversary chooses to initiate nuclear conflict, we must have forces and a targeting capability so that our response would deny either motive or advantage to the aggressor in further escalating the conflict. (Of course, the prospect of our having such a capability would help deter the attack in the first place.) This objective has already in past years resulted in development of a wide range of combinations of targeting and systems selection options. While designed to strength deterrence and control escalation if deterrence were to fail, these options may allow us to adjust our planning so as to reduce the danger of climatic effects as our understanding of them develops.

There are those who argue, in effect, that we no longer need to maintain deterrence as assiduously as we have, because the posited 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. As summarized above, there is large uncertainty as to the extent of those effects; certainly today we cannot be confident that the Soviets would expect such effects to occur as a result of all possible Soviet attacks that we may need to deter. This entire area of consideration--the impact on the deterrence of possible climatic effects--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. (Soviet handling of the "nuclear winter" issue is discussed more fully later in this report.)

The United States has, or is now taking, specific actions which relate directly to maintaining and strengthening deterrence and reducing the dangers of nuclear war: the President's Strategic Modernization Program, arms reductions initiatives, and the Strategic Defense Initiative all bear directly on effective deterrence, and are all therefore relevant to the potential destructiveness of nuclear war including possible climatic effects. We will now discuss these in turn.

Strategic Modernization Program: The President's Strategic Modernization Program is designed to maintain effective deterrence, and by doing so, is also an important measure in minimizing the risks of atmospheric or climatic effects. It is providing significantly enhanced command, control, communications and intelligence (C³I) capabilities which, through their increased survivability and effectiveness contribute immeasurably to our ability to control escalation. Survivable C³I contributes to escalation control and thus, as explained above, to mitigation of damage levels (of whatever kind, including possible climatic effects) by reducing pressures for immediate or expanded use of nuclear weapons out of fear that capability for future release would be lost. The improvements to our sea-based, bomber and (with the Scowcroft modifications) land-based legs of our Triad--all intended also to improve survivability and effectiveness--are also essential to maintaining deterrence.

For nonstrategic weapons, our modernization programs have also resulted in increased discrimination through improved accuracy and reduced yield. Beyond that, we have a good beginning on a program to replace some types of nuclear weapons by highly effective, advanced conventional munitions. All of this would contribute to reduction in possible climatic and other global effects of nuclear war. The possibility of such effects, of course, adds urgency to the implementation of these programs.

Arms Reductions: It is the position of this Administration that the level of nuclear weapons which exists today is unacceptably high. As a result, to the extent it is possible to reduce nuclear weapons unilaterally--particularly where both conventional and nuclear modernization programs allow replacement of existing systems on a less than one-for-one basis--we have undertaken to do so. But it would be misleading to suggest that dramatic reductions in nuclear weapons can be achieved by unilateral U.S. initiatives without increasing the risk of nuclear attack, in the absence of any indication that the Soviet Union is undertaking similar steps, or short of a changed strategic situation resulting from highly effective strategic defenses

Major reductions in nuclear weapons can only be achieved by negotiating mutual and verifiable reduction agreements. Agreements which only legitimate the growth, or slow the rate of increase, of existing stockpiles are not in our national interest. It is for this reason that agreements like SALT II are not acceptable. Since 1981, the Reagan Administration has demonstrated its strong desire to break with the past pattern of calling build-ups "arms control". The arms reduction proposals we have put forward have been the most extensive ones advanced by either side for over 20 years. In the area of INF, we initially

proposed the elimination of all longer-range INF missiles--SS-20s, SS-4s, Pershing IIs, and ground-launched cruise missiles. While this remains our goal, we are prepared, as an intermediate step, to reach agreement on the strategic reduction of U.S. and Soviet LRINF missiles. With regard to strategic weapons, we proposed reducing the number of each side's land-based and sea-based ballistic missile warheads to 5,000--a cut of approximately 33%. We have also called for equal limitations on bomber forces and restrictions on missile throw weight. As we prepare to resume negotiations with the Soviet Union in Geneva, we reaffirm our intention to seek agreements in both areas providing for significant, mutual and verifiable reductions.

As to how nuclear arms reductions bear on nuclear-induced climatic changes, the relationship is two-fold: they can strengthen deterrence--the most direct way available to us today of dealing with the possibility of severe climatic effects--and they can mitigate the effects to some extent if deterrence were to fail. However, nuclear arms reductions which may be achievable in the near term are not likely to be able to reduce significantly the consequences of a nuclear war in which a large proportion of the then existing nuclear forces would be used and in which active defenses would be non-existent or ineffective.

It is worth noting in this context, that proposals which would "freeze" development of modernized systems would also stop what has been a continuing trend in our capability--development of systems which are more discriminating and thus more restrictive in both local and global effects. We must avoid constraints that would force us to use weapons of high yield or unconfined effects.

The Strategic Defense Initiative and Arms Control: It is essential to keep potential benefits of arms reductions clearly in view when assessing what one seeks to accomplish through that process. Our objectives in arms reductions are to preserve deterrence in the near-term and begin a transition to a more stable world, with greatly reduced levels of nuclear arms and an enhanced ability to deter war based upon the increasing contribution of non-nuclear defenses against offensive nuclear arms. This period of transition could lead to the eventual elimination of all nuclear arms, both offensive and defensive. A world free of nuclear arms is an ultimate objective to which we, the Soviet Union, and all other nations can agree. The Strategic Defense Initiative research program enhances our efforts to seek verifiable reductions in offensive weapons through arms control negotiations. Such defenses would destroy nuclear weapons before they could reach their targets, thereby multiplying the gains made through negotiated reductions. Indeed, even a single-layer defense may provide a greater mitigating effect on atmospheric consequences than could result from any level of reductions likely to be accepted by the USSR in the near term.

In addition to its ability to destroy nuclear weapons in flight, the Strategic Defense Initiative would further serve to remove any potential for environmental disaster by moving away from the concept of deterring nuclear war by threat of retaliation and, instead, moving towards deterrence by denial of an attackers political and military objective. Defenses can provide such a deterrent in two ways. First, by destroying a large percentage of Soviet ballistic missile warheads, an effective defense for the U.S. and our Allies can undermine the confidence of Soviet military planners in their ability to predict

the outcome of an attack on our military forces. No rational aggressor is likely to contemplate initiating a nuclear war, even in crisis circumstances, while lacking confidence in his ability to predict success.

Second, by reducing or eliminating the utility of Soviet shorter-range ballistic missiles which threaten all of NATO Europe, defenses can have a significant impact on deterring Soviet aggression against our Allies. Soviet SS-20s and shorter-range ballistic missiles provide overlapping capabilities to target all of Europe. This capability is combined with a Soviet doctrine which stresses the use of conventionally-armed ballistic missiles to initiate rapid and wide-ranging attacks on crucial NATO military assets. By reducing or eliminating the military effectiveness of such ballistic missiles, defense systems have the potential for enhancing deterrence not only against intercontinental nuclear attack, but against nuclear and conventional attacks in Europe as well.

Some critics claim that the SDI program would cause the Soviet Union to increase numbers of weapons in an attempt to overcome the defense. This is related to the argument advanced over a decade ago that, by rendering ourselves totally vulnerable to Soviet weapons we would be able to negotiate limits on those weapons. This logic has, of course, been disproven by events; despite the fact that the U.S. made itself fully vulnerable, the U.S.S.R. increased the number of its weapons fourfold since the signing of the ABM Treaty in 1972. The guarantee that all Soviet weapons would reach their U.S. targets apparently did not give the Soviets an incentive to negotiate an equitable SALT II agreement, it encouraged them to build more weapons. Defenses would have the opposite effect; they would reduce the military and political value of ballistic missiles thereby increasing the likelihood of negotiated reductions. The prospect that powerful emerging technologies will reverse the cost leverage which offensive forces have heretofore had over defenses will further improve the likelihood of negotiated reductions.

Thus, by preventing the detonation of thousands of nuclear warheads, and, by paving the way for the elimination of those warheads by making them obsolete, the Strategic Defense Initiative may provide an answer to both the short-term and potential longer-term consequences of nuclear war.

Civil Defense: As to changes in our Civil Defense posture, the Federal Emergency Management Agency believe that until scientific knowledge regarding climatic impacts of nuclear conflicts is more fully developed it would be impractical to develop cost-effective policies regarding civil defense, or to change existing policies. The basic goal of civil defense in the United States is to develop and maintain a humanitarian program to save lives in the event of major emergency, including a nuclear war.

The particular staff elements within the Federal Emergency Management Agency responsible for civil defense planning are being kept abreast of the issues relative to possible climate effects as they develop and will be prepared to take appropriate action as soon as the relevant research now underway is complete.

As we have shown, much of our long standing policy and our current initiatives are of a nature such as to reduce concern for climatic and other widespread effects, even though the particular phenomena at issue were not known at the time they were instituted. Strong deterrence augmented by necessary force modernization and truly effective arms control to prevent nuclear war; the continuing development of discriminating systems, options for escalation control, and rejection of population targeting to minimize the damage effects not necessary for deterrence, if deterrence were to fail; and finally the Strategic Defense Initiative--all these things work together in the right direction.

Possible Further Initiatives: As we have already pointed out, reducing unwanted damage must be an important feature of our policy. It would be entirely consistent with our policy and recent practices to continue to make weapons more discriminating, to reduce their yields by improved accuracy where possible, and in other ways to minimize effects not directly related to target damage, so as to both enhance the credibility of our deterrent and to reduce unwanted destruction, including the potential for ameliorating possible climatic and other environmental effects. In fact, we are pursuing such objectives in general, though programs are in various stages of development.

Beyond these continuing trends, with regard to targeting and the detailed characteristics of the nuclear forces, which pertain both to deterrence and to limiting damage, it is prudent to develop other measures based on our understanding of long-term climate effects and intended to reduce those effects if deterrence were to fail. Besides possibly adding targeting options to those which already exist to limit damage, some technical developments might also contribute. For example, highly accurate, maneuverable reentry vehicles and earth penetrating weapons, both of which might be useful in strengthening deterrence, could reduce yields and in other ways limit the starting of fires. In the farther future, for selected missions, nonnuclear systems could replace strategic nuclear systems, as we have begun to do for non-strategic systems.

Today, however, we have inadequate knowledge to evaluate all possible measures. As the analytical methods for assessing climatic effects become more accurate and we gain confidence, they can be used to predict what kind of changes will in fact reduce the dangers of nuclear war. For example, some have suggested that reducing the height of burst of the nuclear explosions could reduce the area of thermal effect and, therefore, the amount of material burnt. However, at lower heights of burst, increased fallout might be worse than any mitigation of long-term change in the climate. Where such trade-offs are involved, we need better information before deciding.

4. Soviet Perceptions of Climatic Effects

Soviet science spokesmen and media have claimed that Soviet scientists had independently confirmed the probability of severe long-term atmospheric effects as a consequence of nuclear exchange. Initially, their claim was accepted in the West; however, an examination of open Soviet publications specifically discussing this prediction shows their claim to be unfounded.

In their writings on the "nuclear winter" hypothesis, Soviet scientists have neither used independent scenarios nor provided independent values of the essential parameters characterizing the key ingredients (soot, ash, and dust) on which the hypothesis principally depends. Instead, Soviet researchers--and on this subject, it is hard to tell the difference between scientific workers and propagandists--have uncritically used only the worst-case scenarios and estimates from other work. They have taken these estimates and merely adapted them to borrowed mathematical simulations of state-of-the-art multi-dimensional models of global atmospheric circulation modified to instantaneously simulate long-term global effects after an exchange. For example, the primary atmospheric circulation model used by the Soviets in the case of the widely publicized study by Soviet researchers V. Aleksandrov and G. Stenchikov, is based on a borrowed, obsolete, U.S. model. Thus, given the sources of inputs and methods for their "studies," their findings do not represent independent verifications of the hypothesis.

Further, Soviet reports tend to stretch the conclusions well beyond what even their uncritical, worst-case assessments support, embellishing statements of technical analyses with conclusions that any use of nuclear weapons at all will lead to the disappearance of the human race or similar propagandistic statements the Soviet Union has made on and off for years, even before these atmospheric phenomena surfaced.

The Soviet scientists have contributed very little to the international study or understanding of this phenomenon. This shortfall has not gone unnoticed by other non-Soviet scientists, some of whom have characterized their analyses as "crude" and "flawed." Time after time their presentations contain exaggerated claims, which are criticized by their foreign colleagues following the formal briefing, but subsequent presentations do not reflect any change, even though in private the Soviets acknowledge the exaggeration.

This is not to say that, over the years, the Soviets have not published studies that have examined various effects and phenomena (dust, fires, soot, etc.) of nuclear detonations; they have. However, the Soviets have made little use of such findings in their public discussions and models of the phenomenology associated with the current climate effects hypothesis. They have not been forthcoming in providing information that might have been of use with regard to reducing the uncertainties associated with the assumptions made in their work. Repeatedly, they ignored an American request for information derived from Soviet pre-1963 nuclear tests and large-scale fires. The flow of useful technical work has been almost all one-way. It is worth noting that Soviet interest in this topic provides them with some degree of additional access to U.S. scientists (and their technology) who are involved with super-computers, software model development, and global and mesoscale climate phenomenology.

If the Soviets see this issue as a matter that might substantially affect their policies, strategy, or force structure, those views have so far been hidden from us. It is important that, whatever the outcome of the scientific work regarding climatic effects of nuclear war, the understanding should be commonly held by all of the nuclear powers and help to reduce the risk of nuclear destruction. Unfortunately, recent Soviet performance and statements on the subject do not appear supportive of establishing a truly common understanding, either on the phenomena themselves or on their implications for the strategic relationship between the two powers. If the Soviet leadership believes that the possibility of severe climatic effects is important, then this issue will add its weight, along with the many other imperatives which the United States and the people of the world feel so strongly, to produce a truly constructive approach toward a world in which the fears aroused by such horrors as nuclear war or the so-called "nuclear winter" will be a thing of the past.

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

FROM: Willaim A. Nierenberg
San Diego, CA

DATED: September 24, 1984

SUBJECT:

A letter to Dr. Keyworth concerning a press conference they held in June sponsored by OSTP releasing your recommendations-- which have remained unchanged ever since.

RECEIVED:

October 1, 1984

ACTION BY:

Executive Director/vsh

ACTION COPY TO:

Lynch

INFORMATION COPIES TO:

Abell

Kornack/Pestorius

K Read

File "Nuclear Winter" M/G

SUSPENSE DATE:

October 21, 1984

REMARKS: FOR APPROPRIATE ACTION

Please indicate action taken below and include date of action.
If written correspondence was sent, please attach a copy.

- () Written correspondence.
- () Telecon.
- () Action transferred to _____.
- () No action necessary.
- () Other

File Nucl. Winter

UNIVERSITY OF CALIFORNIA, SAN DIEGO

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO



SANTA BARBARA • SANTA CRUZ

DAVID P. GARDNER
President of the University

WILLIAM A. NIERENBERG
Director
Scripps Institution of Oceanography

LA JOLLA, CALIFORNIA 92093

Phone: (619) 452-2826

Cable: SIOCEAN

TWX: 910-337-1271

September 24, 1984

Dr. George A. Keyworth, II
Science Advisor to the President
Office of Science and Technology Policy
Executive Office of the President
Washington, D.C. 20506

Dear Jay:

I just came back from a long trip to Turkey, and I am on my way to China like you. I was greeted by a huge number of press clippings on acid rain on my return.

Several of them cited Bruce Abell that our Committee went beyond our terms of reference in making the recommendations that we did. That is simply and flatly not true.

If you will remember in June, 1983 we used your personal office to hold a press conference sponsored by OSTP releasing our recommendations--which have remained unchanged ever since. Those recommendations were reviewed and approved by your office. The original terms of reference had been augmented by John Marcum--presumably with your approval.

I hope you have a good week in China.

Sincerely,

Bill N.
William A. Nierenberg

SCRIPPS INSTITUTION OF OCEANOGRAPHY
UNIVERSITY OF CALIFORNIA, SAN DIEGO
DIRECTOR'S OFFICE A-010
LA JOLLA, CALIFORNIA 92093

LOS ANGELES
DROP SHIPMENT
AUTHORIZATION 153
PRESORTED FIRST-CLASS



Dr. George A. Keyworth, II
Science Advisor to the President
Office of Science and Technology Policy
Executive Office of the President
Washington, D.C. 20506

Neil. W. H.

THE WHITE HOUSE

WASHINGTON

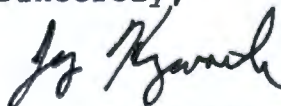
March 8, 1985

Alan
Dear Dr. Hecht:

I would like to thank you for all your efforts in supporting our "nuclear winter" research program. The interagency research plan that was developed under your supervision was well done and will be invaluable in structuring the interagency research program. It not only identifies the specific deficiencies in knowledge of the science areas associated with atmospheric effects of nuclear weapons but also proposes a sound plan to fill those voids. I would also like to thank you for your continuing support of our program by providing expert technical advice and acumen into the various interrelationships of the science community and the bureaucracy.

Thank you again for all your work. Your assistance was crucial in getting this program started.

Sincerely,



G. A. Keyworth
Science Advisor to the President

Dr. Alan Hecht
National Climate Program Office
11400 Rockville Pike
Suite 108
Rockville, Maryland 20852

cc: Dr. Anthony Calio

THE WHITE HOUSE
WASHINGTON

January 25, 1985

Bud,
Dear Mr. ~~Brown~~:

Enclosed is a copy of my memorandum which confirms the discussions of the 17 January 1985 meeting and subsequent agreements with the Department of Defense. The only change from the meeting is that my office will provide the chairman for the coordinating committee, which is still in keeping with the intent of all concerned.

I have also enclosed a copy of the National Climate Program Office's report which includes our final revisions of the interagency research plan. In keeping with our agreed course of action, it is necessary to have 50 copies of the final revised plan for the announcement of the interagency research program on or about 5 February 1985. Xerox copies would be sufficient for this purpose. A larger number of copies is necessary for the wide dissemination that can be expected once the program gets under way.

If you have any questions concerning our revisions, please call upon me or my staff at any time. Thank you for your assistance.

Yours truly,



G. A. Keyworth
Science Advisor to the President

The Honorable
Clarence J. Brown
Deputy Secretary of Commerce
Washington, DC 20230

Enclosure

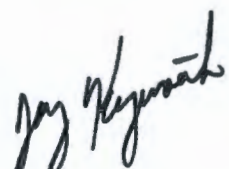
THE WHITE HOUSE

WASHINGTON

January 25, 1985

MEMORANDUM FOR DISTRIBUTION

FROM: JAY KEYWORTH



SUBJECT: Decisions on "Nuclear Winter" Research Program

This memorandum confirms the discussions of the January 17, 1985 meeting on the issue of a "nuclear winter" research program and the subsequent agreements made between the interested parties. The following represent the agreed course of action:

1. There will be an Administration sponsored scientific research program to respond to the "nuclear winter" issue.
2. The DOD and DOE will augment their on-going research effort on the "nuclear winter" phenomenon for FY-86 from a combined total of \$3.5 million to a combined total of \$5.0 million. Each will contribute approximately half of the total, the exact split to be jointly determined.
3. NSF will sponsor \$500 thousand worth of research on the "nuclear winter" phenomenon in FY 86.
4. The research program proposed by the National Climate Program Office in their draft report will be revised so as not to conflict with these decisions. All reference to the budget in the research plan will be removed from the document.
5. There will be an interagency coordinating committee to oversee the research program. The committee will have representation from DOD, DOE, DOC, NSF and OSTP with ex officio members from NSC and OMB. OSTP will chair the committee.

6. This "nuclear winter" research program will be known as "The Interagency Research Program".
7. Announcement of the Interagency Research Program will be made by limited comments included in Dr. Keyworth's press conference on the science portion of the President's budget which normally occurs shortly after the budget presentation to Congress and by testimony to be given by DOD to Congress in March 1985.

The following terms of reference apply to the above stated decisions:

1. This research program will only address science questions. Policy issues will be avoided in discussions related to the science research effort.
2. Program funds used to conduct this research will be administered by the respective agencies sponsoring the research.
3. The coordinating committee will be an advisory body only. They will make recommendations on research topics to be pursued and facilitate the flow of information. The chairman of the committee will be the focal point for administrative matters and communication with the press and Congress on the science aspects of the program. Policy matters will remain the responsibility of the appropriate agencies.

Distribution:

The Honorable Clarence J. Brown
The Honorable Richard N. Perle
Dr. Richard Wagner
Ronald F. Lehman
Donald Ofte
Dr. Richard S. Nicholson
Robert E. Howard

K FYI RJA

TR

ACTION ITEMS
FOR
POLICY RELATED TO NUCLEAR WINTER

On 30 October 1984 a Nuclear Winter Policy Planning meeting was held in the NEOB with representatives of NSC (Bob Linhard), OMB (Bob Howard), OSTP (Maurie Roesch) and NOAA (Alan Hecht) in attendance. The following policy actions were agreed to:

Budget Formulation: A decision paper will be formulated to address the budget for the Nuclear Winter Research Program. Questions to be addressed will be: Who pays? How much? When does the program start? OMB will have the lead and is supported by OSTP. Action is projected to be completed by 30 November 1984.

Science Contacts with Soviets: Alan Hecht will brief NSC, OSTP and State on the history and on-going activities of environmental research with the Soviets. This will be completed in the next few weeks.

Program Management: Alan Hecht will develop program management options for the Nuclear Winter research effort. These options will be coordinated with NSC, OMB, etc. then Dr. Keyworth will be briefed.

Briefing on Research Plan: Alan Hecht will brief the policy Mafia on the Nuclear Winter Science Research Program. Bob Linhard will coordinate this.

Sagan C., and
Nuch winter
Nuch. Winter

JK

THE WHITE HOUSE
WASHINGTON

October 9, 1984

Dear Dr. Sagan:

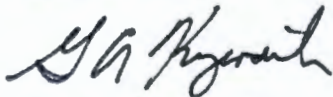
Thank you for your letter concerning both the public reactions to the study of nuclear winter phenomena (i.e., Turner's editorial), and for the need to better articulate such a study's purpose and direction. I'm afraid that I too must admit a certain level of frustration with head-in-the-sand philosophies such as that recommended by Reverend Turner. Too many people fail to realize that decisionmakers have necessarily become inured, and therefore tend to move very cautiously, on recommendations based upon doomsday predictions, regardless of how well initially documented.

As a result, I always find a "we don't need to know anymore" attitude to be counter productive. If decisionmakers are to act, they need broadly based expert consensus which has fully explored the problem, time to internalize the results, and at least some semblance of practical alternatives from which to choose.

Because of the central role of climatology in any nuclear winter discussion, NOAA has offered to begin an independent preliminary assessment of the issues. They intend to report their initial findings and recommend the context and content of any follow-on national program in time for a well planned start subsequent to the 1985 fiscal year. To this extent I believe it would therefore be drastically premature to preface such a recommendation with discussion of its implications on doctrine and policy. Right or wrong, such discussions would have to be the result of the actual findings of any meaningful research effort. To do so earlier would not only be tilting at windmills, but might actually have an adverse

effect by appearing to prejudge study findings much like the Reverend Turner has done. I think you and I would agree that any such perception could have a very deleterious effect on what could otherwise be an extremely important piece of work. Your recommendation that a parallel study concerning the ecological effects of macro-changes in weather patterns might, however, have much broader utility than just the implications of global winter. I would accordingly lean toward experimental/analytical parameters which include, but are not necessarily limited by, preliminary nuclear winter boundary conditions. Such a broader effort could, as you suggest, be carried out independently of what could otherwise become a very controversial climatological study and be of benefit regardless of the results of that study. I would therefore be very much interested in hearing your suggestions along this line.

Sincerely,



G. A. Keyworth
Science Advisor to the President

Professor Carl Sagan
Cornell University
Ithaca, New York 14853-0355

CORNELL UNIVERSITY
Center for Radiophysics and Space Research

SPACE SCIENCES BUILDING
Ithaca, New York 14853 - 0355

Telephone (607) 256-4971

9 September 1984

Laboratory for Planetary Studies

Dr. George Keyworth
Director,
Office of Science and Technology Policy
Executive Office Building
Washington, DC 20506

Dear Dr. Keyworth:

I have recently heard from a [REDACTED] who are [REDACTED] at the mere existence of a [REDACTED] on the grounds that we already know that the consequences of nuclear war are bad enough. The [REDACTED] from the Lexington Herald-Leader of August 19, 1984 is [REDACTED]. At the very least, these comments underscore the importance of an absolutely [REDACTED] in the report [REDACTED]. It seems to me there should be some discussion, even though this is at the very beginning of the study, of [REDACTED]. There are a wide range of possible implications, many of which are laid out in my Foreign Affairs article (and not all of which -- including [REDACTED]).

I'd like also to second the point in George Woodwell's August 24th letter to you. The proposed National Research Plan should incorporate a major study of the relevant ecology and biology, but of course, under more appropriate auspices than NOAA. There are a wide range of possible studies, paralleling those in the climate program -- ranging experimentally from one organism to a whole microcosm of organisms subjected to simulated Nuclear Winter conditions, and in theory, including full-scale computer

Step 2
Climatology

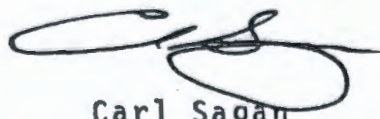
Dr. George Keyworth
9 September 1984
page 2

reprints

simulations of the appropriate population biology under stressed conditions. Such research would also help in improving our understanding of a number of problems in whole organism biology and general ecology, and would help to moderate some criticisms of the National Research Plan. You can see from the enclosed paper by Ehrlich, et al. some hint of the range of biological factors that must enter into assessing the implication to Nuclear Winter for living systems. The more severe and prolonged the Nuclear Winter is, the less detailed the biological studies might have to be. But ~~if~~ comparatively mild Nuclear Winters are possible, very detailed biological studies are called for. These ecological studies seem very important, and should be carried out ~~in parallel~~, and not in series with, the climatic effects research plan.

With best wishes,

Cordially,



Carl Sagan
David Duncan Professor of Astronomy
and Space Sciences,
and Director, Laboratory for
Planetary Studies

CS/np
Enclosures

cc: A. Hecht
G. White
P. Raven
F. Press
R. Peterson
P. Ehrlich
R. Turco
B. Toon
T. Ackerman
J. Pollack

CORNELL UNIVERSITY
Center for Radiophysics and Space Research

SPACE SCIENCES BUILDING
Ithaca, New York 14853 - 0355

Telephone (607) 256-4971

9 September 1984

Laboratory for Planetary Studies

Dr. George Keyworth
Director,
Office of Science and Technology Policy
Executive Office Building
Washington, DC 20506

Dear Dr. Keyworth:

I have recently heard from a number of people who are dismayed at the mere existence of a National Research Plan to study Nuclear Winter, on the grounds that we already know that the consequences of nuclear war are bad enough. The enclosed column from the Lexington Herald-Leader of August 19, 1984 is more or less typical. At the very least, these comments underscore the importance of an absolutely clear statement in the report on what use the five year study plan will be. It seems to me there should be some discussion, even though this is at the very beginning of the study, of how Nuclear Winter might affect doctrine and policy. There are a wide range of possible implications, many of which are laid out in my Foreign Affairs article (and not all of which -- including the reconfiguration of arsenals to lower yield, higher accuracy burrowing warheads -- I agree with).

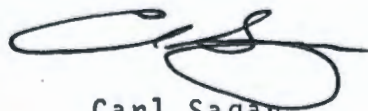
I'd like also to second the point in George Woodwell's August 24th letter to you. The proposed National Research Plan should incorporate a major study of the relevant ecology and biology, but of course, under more appropriate auspices than NOAA. There are a wide range of possible studies, paralleling those in the climate program -- ranging experimentally from one organism to a whole micro-cosm of organisms subjected to simulated Nuclear Winter conditions, and in theory, including full-scale computer

Dr. George Keyworth
9 September 1984
page 2

simulations of the appropriate population biology under stressed conditions. Such research would also help in improving our understanding of a number of problems in whole organism biology and general ecology, and would help to moderate some criticisms of the National Research Plan. You can see from the enclosed paper by Ehrlich, et al. some hint of the range of biological factors that must enter into assessing the implication to Nuclear Winter for living systems. The more severe and prolonged the Nuclear Winter is, the less detailed the biological studies might have to be. But if comparatively mild Nuclear Winters are possible, very detailed biological studies are called for. These ecological studies seem very important, and should be carried out in parallel to, and not in series with, the climatic effects research plan.

With best wishes,

Cordially,



Carl Sagan
David Duncan Professor of Astronomy
and Space Sciences,
and Director, Laboratory for
Planetary Studies

CS/np
Enclosures

cc: A. Hecht
G. White
P. Raven
F. Press
R. Peterson
P. Ehrlich
R. Turco
B. Toon
T. Ackerman
J. Pollack

Federal study of nuclear winter theory wastes time and money

6005A Nuclear Winter
Reading that opening sentence started my day with a sickening feeling: "The federal government has embarked on a broad program to assess the theory that fires set by even a limited exchange of nuclear weapons would blot out so much sunlight with smoke and soot that life on Earth would be all but extinguished" (Herald-Leader, Aug. 9, 1984).

That's a mind-boggler! Somewhere in the labyrinthine recesses of Potomac bureaucracy, there are supposedly straight-faced and sober people in a dozen agencies who are preparing to spend up to 50 million tax dollars over the next five years to test a theory which cannot really be tested — short of nuclear war. Using simulations and experiments — including the burning of buildings, ground areas and "managed" forest fires — the goal is to see whether the now infamous "nuclear winter" scenario is or is not a genuine threat.

Can you believe this? For 30 years we've been refining and expanding what's become a monstrous nuclear arsenal — now Washington is ready to spend \$50 million just to see how much damage the bloody thing can really do. A boon to scientific inquiry? It sounds more like a boondoggle at taxpayers' expense.

**William
Turner**

Herald-Leader
community columnist



The truth is that sufficient research has already been done within the scientific community, and at considerably less expense. Experts from several nations (including the United States and the Soviet Union) contributed to *Aftermath — The Human and Ecological Consequences of Nuclear War*, published in 1983 by the Royal Swedish Academy of Scientists. The nuclear winter theory, put forward by Carl Sagan and other distinguished researchers, has been summarized in a 35-page journal article in *Foreign Affairs* (Winter, 1983-84). Jonathan Schell's *Fate of the Earth*, despite some weaknesses, has received strong scientific backing for its basic diagnoses. Then there is Harvard Medical School's Dr. Howard Hiatt's well-known labeling of nuclear war as "the last epidemic," along with his studied assessment of the uselessness of treatment programs in the wake of nuclear exchange.

Enough already! A deficit-ridden

federal government has no business adding to these data of destruction. Massive and instant death, firestorms, radiation sickness, irreparable damage to the ozone layer, and eventual deterioration of the ecosystem are all as proved and predictable as possible, without the acid test of an actual strike.

What, then, is the purpose of this futile, government-backed effort? Will it lead to disarmament or to increased deployment? Is there anything worth knowing that we don't already know about nuclear war which can justify such an outrageous outlay of public funds?

When it comes to doling out the dollars for questionable research, nobody does it better than Uncle Sam. And when it comes to nuclear arms, J.H. Wheelock sees us humans pretty clearly:

"A planet doesn't explode of itself," said dryly
The Martian astronomer gazing off into the air.

"That they were able to do it is proof that highly
Intelligent beings must have been living there.

Sometimes, folks, I wonder ...

William L. Turner is pastor of Central Baptist Church in Lexington.

Nuclear Winter: Global Consequences of Multiple Nuclear Explosions

R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, and Carl Sagan

Long-Term Biological Consequences of Nuclear War

Paul R. Ehrlich, John Harte, Mark A. Harwell, Peter H. Raven, Carl Sagan, George M. Woodwell, Joseph Berry, Edward S. Ayensu, Anne H. Ehrlich, Thomas Eisner, Stephen J. Gould, Herbert D. Grover, Rafael Herrera, Robert M. May, Ernst Mayr, Christopher P. McKay, Harold A. Mooney, Norman Myers, David Pimentel, and John M. Teal

With the Compliments of The Center on the Consequences of Nuclear War

The findings presented herein were first made public at the Conference on the World After Nuclear War, 31 October-1 November 1983, Washington, D.C. The preliminary findings had been submitted to review at scientific meetings involving more than 100 scientists and held under the auspices of the Conference, Cambridge, Massachusetts in April, 1983.

Because of the extreme importance of this and other recent work on the atmospheric and biological consequences of nuclear war, The Center on the Consequences of Nuclear War was established in December 1983 to carry the information presented at the Conference to a broad public in the United States and worldwide. Working through other organizations and through the media, The Center makes available information and materials (print and audiovisual) based on the most recent scientific studies of the world after nuclear war.

*The Center on the Consequences of Nuclear War
3244 Prospect St., N.W.
Washington, DC 20007
Tel: (202) 337-4706*

Nuclear Winter: Global Consequences of Multiple Nuclear Explosions

R. P. Turco, O. B. Toon, T. P. Ackerman
J. B. Pollack, Carl Sagan

Concern has been raised over the short- and long-term consequences of the dust, smoke, radioactivity, and toxic vapors that would be generated by a nuclear war (1-7). The discovery that

quantities of sooty smoke that would attenuate sunlight and perturb the climate. These developments have led us to calculate, using new data and improved models, the potential global environmen-

Summary. The potential global atmospheric and climatic consequences of nuclear war are investigated using models previously developed to study the effects of volcanic eruptions. Although the results are necessarily imprecise, due to a wide range of possible scenarios and uncertainty in physical parameters, the most probable first-order effects are serious. Significant hemispherical attenuation of the solar radiation flux and subfreezing land temperatures may be caused by fine dust raised in high-yield nuclear surface bursts and by smoke from city and forest fires ignited by airbursts of all yields. For many simulated exchanges of several thousand megatons, in which dust and smoke are generated and encircle the earth within 1 to 2 weeks, average light levels can be reduced to a few percent of ambient and land temperatures can reach -15° to -25°C . The yield threshold for major optical and climatic consequences may be very low: only about 100 megatons detonated over major urban centers can create average hemispheric smoke optical depths greater than 2 for weeks and, even in summer, subfreezing land temperatures for months. In a 5000-megaton war, at northern mid-latitude sites remote from targets, radioactive fallout on time scales of days to weeks can lead to chronic mean doses of up to 50 rads from external whole-body gamma-ray exposure, with a likely equal or greater internal dose from biologically active radionuclides. Large horizontal and vertical temperature gradients caused by absorption of sunlight in smoke and dust clouds may greatly accelerate transport of particles and radioactivity from the Northern Hemisphere to the Southern Hemisphere. When combined with the prompt destruction from nuclear blast, fires, and fallout and the later enhancement of solar ultraviolet radiation due to ozone depletion, long-term exposure to cold, dark, and radioactivity could pose a serious threat to human survivors and to other species.

dense clouds of soil particles may have played a major role in past mass extinctions of life on Earth (8-10) has encouraged the reconsideration of nuclear war effects. Also, Crutzen and Birks (7) recently suggested that massive fires ignited by nuclear explosions could generate

tal effects of dust and smoke clouds (henceforth referred to as nuclear dust and nuclear smoke) generated in a nuclear war (11). We neglect the short-term effects of blast, fire, and radiation (12-14). Most of the world's population could probably survive the initial nuclear

exchange and would inherit the postwar environment. Accordingly, the longer-term and global-scale aftereffects of nuclear war might prove to be as important as the immediate consequences of the war.

To study these phenomena, we used a series of physical models: a nuclear war scenario model, a particle microphysics model, and a radiative-convective model. The nuclear war scenario model specifies the altitude-dependent dust, smoke, radioactivity, and NO_x injections for each explosion in a nuclear exchange (assuming the size, number, and type of detonations, including heights of burst, geographic locales, and fission yield fractions). The source model parameterization is discussed below and in a more detailed report (15). The one-dimensional microphysical model (15-17) predicts the temporal evolution of dust and smoke clouds, which are taken to be rapidly and uniformly dispersed. The one-dimensional radiative-convective model (1-D RCM) uses the calculated dust and smoke particle size distributions and optical constants and Mie theory to calculate visible and infrared optical properties, light fluxes, and air temperatures as a function of time and height. Because the calculated air temperatures are sensitive to surface heat capacities, separate simulations are performed for land and ocean environments, to define possible temperature contrasts. The techniques used in our 1-D RCM calculations are well documented (15, 18).

Although the models we used can provide rough estimates of the average effects of widespread dust and smoke clouds, they cannot accurately forecast short-term or local effects. The applicability of our results depends on the rate and extent of dispersion of the explosion clouds and fire plumes. Soon after a large nuclear exchange, thousands of individual dust and smoke clouds would be distributed throughout the northern mid-latitudes and at altitudes up to 30 km.

R. P. Turco is at R & D Associates, Marina del Rey, California 90291; O. B. Toon, T. P. Ackerman, and J. B. Pollack are at NASA Ames Research Center, Moffett Field, California 94035; and Carl Sagan is at Cornell University, Ithaca, New York 14853.

Horizontal turbulent diffusion, vertical wind shear, and continuing smoke emission could spread the clouds of nuclear debris over the entire zone, and tend to fill in any holes in the clouds, within 1 to 2 weeks. Spatially averaged simulations of this initial period of cloud spreading must be viewed with caution; effects would be smaller at some locations and larger at others, and would be highly variable with time at any given location.

The present results also do not reflect the strong coupling between atmospheric motions on all length scales and the modified atmospheric solar and infrared heating and cooling rates computed with the 1-D RCM. Global circulation patterns would almost certainly be altered in response to the large disturbances in the driving forces calculated here (19). Although the 1-D RCM can predict only horizontally, diurnally, and seasonally averaged conditions, it is capable of estimating the first-order climate responses of the atmosphere, which is our intention in this study.

Scenarios

A review of the world's nuclear arsenals (20-24) shows that the primary strategic and theater weapons amount to $\approx 12,000$ megatons (MT) of yield carried by $\approx 17,000$ warheads. These arsenals are roughly equivalent in explosive power to 1 million Hiroshima bombs. Al-

though the total number of high-yield warheads is declining with time, about 7000 MT is still accounted for by warheads of > 1 MT. There are also $\approx 30,000$ lower-yield tactical warheads and munitions which are ignored in this analysis. Scenarios for the possible use of nuclear weapons are complex and controversial. Historically, studies of the long-term effects of nuclear war have focused on a full-scale exchange in the range of 5000 to 10,000 MT (2, 12, 20). Such exchanges are possible, given the current arsenals and the unpredictable nature of warfare, particularly nuclear warfare, in which escalating massive exchanges could occur (25).

An outline of the scenarios adopted here is presented in Table 1. Our baseline scenario assumes an exchange of 5000 MT. Other cases span a range of total yield from 100 to 25,000 MT. Many high-priority military and industrial assets are located near or within urban zones (26). Accordingly, a modest fraction (15 to 30 percent) of the total yield is assigned to urban or industrial targets. Because of the large yields of strategic warheads [generally ≈ 100 kilotons (KT)], "surgical" strikes against individual targets are difficult; for instance, a 100-KT airburst can level and burn an area of ≈ 50 km², and a 1-MT airburst, ≈ 5 times that area (27, 28), implying widespread collateral damage in any "countervalue," and many "counterforce," detonations.

The properties of nuclear dust and smoke are critical to the present analysis. The basic parameterizations are described in Tables 2 and 3, respectively; details may be found in (15). For each explosion scenario, the fundamental quantities that must be known to make optical and climate predictions are the total atmospheric injections of fine dust (≈ 10 μ m in radius) and soot.

Nuclear explosions at or near the ground can generate fine particles by several mechanisms (27): (i) ejection and disaggregation of soil particles (29), (ii) vaporization and renucleation of earth and rock (30), and (iii) blowoff and sweepup of surface dust and smoke (31). Analyses of nuclear test data indicate that roughly 1×10^5 to 6×10^5 tons of dust per megaton of explosive yield are held in the stabilized clouds of land surface detonations (32). Moreover, size analysis of dust samples collected in nuclear clouds indicates a substantial submicrometer fraction (33). Nuclear surface detonations may be much more efficient in generating fine dust than volcanic eruptions (15, 34), which have been used inappropriately in the past to estimate the impacts of nuclear war (2).

The intense light emitted by a nuclear fireball is sufficient to ignite flammable materials over a wide area (27). The explosions over Hiroshima and Nagasaki both initiated massive conflagrations (35). In each city, the region heavily damaged by blast was also consumed by fire (36). Assessments over the past two decades strongly suggest that widespread fires would occur after most nuclear bursts over forests and cities (37-44). The Northern Hemisphere has $\approx 4 \times 10^7$ km² of forest land, which holds combustible material averaging ≈ 2.2 g/cm² (7). The world's urban and suburban zones cover an area of $\approx 1.5 \times 10^6$ km² (15). Central cities, which occupy 5 to 10 percent of the total urban area, hold ≈ 10 to 40 g/cm² of combustible material, while residential areas hold ≈ 1 to 5 g/cm² (41, 42, 44, 45). Smoke emissions from wildfires and large-scale urban fires probably lie in the range of 2 to 8 percent by mass of the fuel burned (46). The highly absorbing sooty fraction (principally graphitic carbon) could comprise up to 50 percent of the emission by weight (47, 48). In wildfires, and probably urban fires, ≈ 90 percent of the smoke mass consists of particles < 1 μ m in radius (49). For calculations at visible wavelengths, smoke particles are assigned an imaginary part of the refractive index of 0.3 (50).

Table 1. Nuclear exchange scenarios.

Case*	Total yield (MT)	Percent of yield			Total number of explosions
		Surface bursts	Urban or industrial targets	Warhead yield range (MT)	
1. Baseline exchange	5,000	57	20	0.1 to 10	10,400
2. Low-yield airbursts	5,000	10	33	0.1 to 1	22,500†
9. 10,000-MT‡ maximum	10,000	63	15	0.1 to 10	16,160
10. 3,000-MT exchange	3,000	50	25	0.3 to 5	5,433
11. 3,000-MT counterforce	3,000	70	0	1 to 10	2,150
12. 1,000-MT exchange§	1,000	50	25	0.2 to 1	2,250
13. 300-MT Southern Hemisphere	300	0	50	1.	300
14. 100-MT city attack¶	100	0	100	0.1	1,000
16. Silos, "severe" case#	5,000	100	0	5 to 10	700
18. 25,000-MT‡ "future war"	25,000	72	10	0.1 to 10	28,300†

*Case numbers correspond to a complete list given in (15). Detailed detonation inventories are not reproduced here. Except as noted, attacks are concentrated in the NH. Baseline dust and smoke parameters are described in Tables 2 and 3. †Assumes more extensive MIRVing of existing missiles and some possible new deployment of medium- and long-range missiles (20-23). ‡Although these larger total yields might imply involvement of the entire globe in the war, for ease of comparison hemispherically averaged results are still considered. §Nominal area of wildfires is reduced from 5×10^5 to 5×10^4 km². ||Nominal area of wildfires is reduced from 5×10^5 to 5×10^3 km². ¶The central city burden of combustibles is 20 g/cm² (twice that in the baseline case) and the net fire smoke emission is 0.026 g per gram of material burned. There is a negligible contribution to the opacity from wildfires and dust. #Includes a sixfold increase in the fine dust mass lofted per megaton of yield.

for optical perturbations on a hemispheric scale appears to lie at $\approx 1 \times 10^8$ tons. From case 14, one can envision the release of $\approx 1 \times 10^6$ tons of smoke from each of 100 major city fires consuming $\approx 4 \times 10^7$ tons of combustible material per city. Such fires could be ignited by 100 MT of nuclear explosions. Unexpectedly, less than 1 percent of the existing strategic arsenals, if targeted on cities, could produce optical (and climatic) disturbances much larger than those previously associated with a massive nuclear exchange of $\approx 10,000$ MT (2).

Figure 2 shows the surface temperature perturbation over continental land areas in the NH calculated from the dust and smoke optical depths for several scenarios. Most striking are the extremely low temperatures occurring within 3 to 4 weeks after a major exchange. In the baseline 5000-MT case, a minimum land temperature of ≈ 250 K (-23°C) is predicted after 3 weeks. Subfreezing temperatures persist for several months. Among the cases shown, even the smallest temperature decreases on land are $\approx 5^\circ$ to 10°C (cases 4, 11, and 12), enough to turn summer into winter. Thus, severe climatological consequences might be expected in each of these cases. The 100-MT city airburst scenario (case 14) produces a 2-month interval of subfreezing land tempera-

tures, with a minimum again near 250 K. The temperature recovery in this instance is hastened by the absorption of sunlight in optically thin remnant soot clouds (see below). Comparable exchanges with and without smoke emission (for instance, cases 10 and 11) show that the tropospheric soot layers cause a sudden surface cooling of short duration, while fine stratospheric dust is responsible for prolonged cooling lasting a year or more. [Climatologically, a long-term surface cooling of only 1°C is significant (60).] In all instances, nuclear dust acts to cool the earth's surface; soot also tends to cool the surface except when the soot cloud is both optically thin and located near the surface [an unimportant case because only relatively small transient warmings ≈ 2 K can thereby be achieved (61)].

Predicted air temperature variations over the world's oceans associated with changes in atmospheric radiative transport are always small (cooling of ≤ 3 K) because of the great heat content and rapid mixing of surface waters. However, variations in atmospheric zonal circulation patterns (see below) might significantly alter ocean currents and upwelling, as occurred on a smaller scale recently in the Eastern Pacific (El Niño) (62). The oceanic heat reservoir would also moderate the predicted continental

land temperature decreases, particularly in coastal regions (10). The effect is difficult to assess because disturbances in atmospheric circulation patterns are likely. Actual temperature decreases in continental interiors might be roughly 30 percent smaller than predicted here, and along coastlines 70 percent smaller (10). In the baseline case, therefore, continental temperatures may fall to ≈ 260 K before returning to ambient.

Predicted changes in the vertical temperature profile for the baseline nuclear exchange are illustrated as a function of time in Fig. 3. The dominant features of the temperature perturbation are a large warming (up to 80 K) of the lower stratosphere and upper troposphere, and a large cooling (up to 40 K) of the surface and lower troposphere. The warming is caused by absorption of solar radiation in the upper-level dust and smoke clouds; it persists for an extended period because of the long residence time of the particles at high altitudes. The size of the warming is due to the low heat capacity of the upper atmosphere, its small infrared emissivity, and the initially low temperatures at high altitudes. The surface cooling is the result of attenuation of the incident solar flux by the aerosol clouds (see Fig. 4) during the first month of the simulation. The greenhouse effect no longer occurs in our calculations because

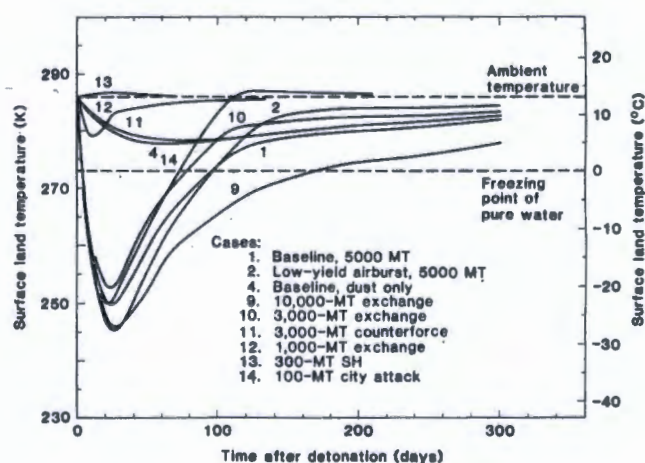
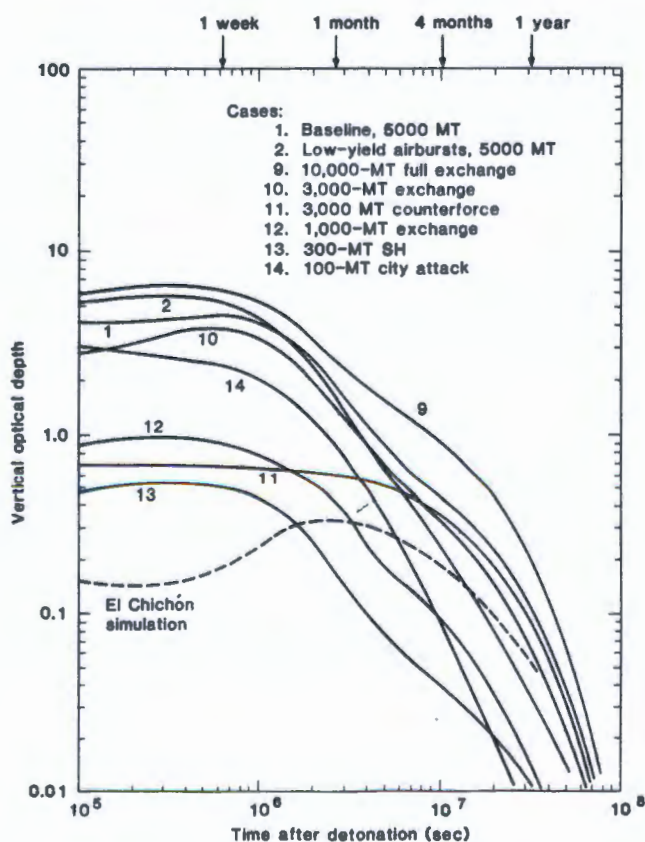


Fig. 1 (left). Time-dependent hemispherically averaged vertical optical depths (scattering plus absorption) of nuclear dust and smoke clouds at a wavelength of 550 nm. Optical depths ≤ 0.1 are negligible, ~ 1 are significant, and > 2 imply possible major consequences. Transmission of sunlight becomes highly nonlinear at optical depths ≈ 1 . Results are given for several of the cases in Table 1. Calculated optical depths for the expanding El Chichón eruption cloud are shown for comparison (53). Fig. 2 (right). Hemispherically averaged surface temperature variations after a nuclear exchange. Results are shown for several of the cases in Table 1. (Note the linear time scale, unlike that in Fig. 1). Temperatures generally apply to the interior of continental land masses. Only in cases 4 and 11 are the effects of fires neglected.

Simulations

The model predictions discussed here generally represent effects averaged over the Northern Hemisphere (NH). The initial nuclear explosions and fires would be largely confined (51) to northern mid-latitudes (30° to 60°N). Accordingly, the predicted mean dust and smoke opacity could be larger by a factor of 2 to 3 at mid-latitudes, but smaller elsewhere. Hemispherically averaged optical depths at visible wavelengths (52) for the mixed nuclear dust and smoke clouds corresponding to the scenarios in Table 1 are shown in Fig. 1. The vertical optical depth is a convenient diagnostic of nuclear cloud properties and may be used roughly to scale atmospheric light levels and temperatures for the various scenarios.

In the baseline scenario (case 1, 5000 MT), the initial NH optical depth is ≈ 4 , of which ≈ 1 is due to stratospheric dust and ≈ 3 to tropospheric smoke. After 1 month the optical depth is still ≈ 2 . Beyond 2 to 3 months, dust dominates the optical effects, as the soot is largely depleted by rainout and washout (54). In the baseline case, about 240,000 km² of urban area is partially (50 percent) burned by ≈ 1000 MT of explosions (only 20 percent of the total exchange yield). This roughly corresponds to one sixth of the world's urbanized land area, one fourth of the developed area of the NH, and one half of the area of urban centers with populations $> 100,000$ in the NATO and Warsaw Pact countries. The mean quantity of combustible material consumed over the burned area is ≈ 1.9 g/cm². Wildfires ignited by the remaining 4000 MT of yield burn another 500,000 km² of forest, brush, and grasslands (7, 39, 55), consuming ≈ 0.5 g/cm² of fuel in the process (7).

Total smoke emission in the baseline case is ≈ 225 million tons (released over several days). By comparison, the current annual global smoke emission is estimated as ≈ 200 million tons (15), but is probably < 1 percent as effective as nuclear smoke would be in perturbing the atmosphere (56).

The optical depth simulations for cases 1, 2, 9, and 10 in Fig. 1 show that a range of exchanges between 3000 and 10,000 MT might create similar effects. Even cases 11, 12, and 13, while less severe in their absolute impact, produce optical depths comparable to or exceeding those of a major volcanic eruption. It is noteworthy that eruptions such as Tambora in 1815 may have produced significant climate perturbations, even

with an average surface temperature decrease of ≈ 1 K (57-60).

Case 14 represents a 100-MT attack on cities with 1000 100-KT warheads. In the attack, 25,000 km² of built-up urban area is burned (such an area could be accounted for by ≈ 100 major cities). The smoke emission is computed with fire parameters that differ from the baseline case. The average burden of combustible material in city centers is 20 g/cm² (versus 10 g/cm² in case 1) and the average

smoke emission factor is 0.026 gram of smoke per gram of material burned (versus the conservative figure of 0.011 g/g adopted for central city fires in the baseline case). About 130 million tons of urban smoke is injected into the troposphere in each case (none reaches the stratosphere in case 14). In the baseline case, only about 10 percent of the urban smoke originates from fires in city centers (Table 3).

The smoke injection threshold for ma-

Table 2. Dust parameterization for the baseline case.

Type of burst	Materials in stabilized nuclear explosion clouds*		
	Dust mass (ton/MT):	Dust size distribution† [r _m (μm)/σ/α]:	H ₂ O (ton/MT):
Land surface	3.3×10^5	0.25/2.0/4.0	1.0×10^5
Land near-surface	1.0×10^5	0.25/2.0/4.0	1.0×10^5

Dust composition: siliceous minerals and glasses

Index of refraction at visible wavelengths‡: $n = 1.50 - 0.001 i$

Stabilized nuclear cloud top and bottom heights, z_t and z_b , for surface and low-air bursts§:

$z_t = 21 Y^{0.2}$; $z_b = 13 Y^{0.2}$; where Y = yield in megatons

Multiburst interactions are ignored

Baseline dust injections

Total dust $\approx 9.6 \times 10^8$ tons; 80 percent in the stratosphere; 8.4 percent < 1 μm in radius

Submicrometer dust injection is ~ 25 ton/KT for surface bursts, which represents ~ 0.5 percent of the total ejecta mass

Total initial area of stabilized fireballs $\approx 2.0 \times 10^6$ km²

*Materials are assumed to be uniformly distributed in the clouds. †Particle size distributions (number/cm³ - μm radius) are log-normal with a power-law tail at large sizes. The parameters r_m and σ are the log-normal number mode radius and size variance, respectively, and α is the exponent of the $r^{-\alpha}$ dependence at large sizes. The log-normal and power-law distributions are connected at a radius of ≈ 1 μm (15). ‡The refractive indices of dust at infrared wavelengths are discussed in (10). §The model of Foley and Rudeiman (87) is adopted, but with the cloud heights lowered by about 0.5 km. The original cloud heights are based on U.S. Pacific test data, and may overestimate the heights at mid-latitudes by several kilometers.

Table 3. Fire and smoke parameterization for the baseline case.

Fire area and emissions	
Area of urban fire ignition defined by the 20 cal/cm ² thermal irradiance contour (≈ 5 psi peak overpressure contour) with an average atmospheric transmittance of 50 percent: A (km ²) = $250 Y$, where Y = yield in megatons detonated over cities; overlap of fire zones is ignored	
Urban flammable material burdens average 3 g/cm ² in suburban areas and 10 g/cm ² in city centers (5 percent of the total urban area)	
Average consumption of flammables in urban fires is 1.9 g/cm ²	
Average net smoke emission factor is 0.027 g per gram of material burned (for urban centers it is only 0.011 g/g)	
Area of wildfires is 5×10^5 km ² with 0.5 g/cm ² of fuel burned, and a smoke emission factor of 0.032 g/g	
Long-term fires burn 3×10^{14} g of fuel with an emission factor of 0.05 g/g	
Fire plume heights (top and bottom altitudes)	
Urban fires: 1 to 7 km	
Fire storms (5 percent of urban fires): $z_b \leq 5$ km; $z_t \leq 19$ km	
Wildfires: 1 to 5 km	
Long-term fires: 0 to 2 km	
Fire duration	
Urban fires, 1 day; wildfires, 10 days; long-term fires, 30 days	
Smoke properties	
Density, 1.0 g/cm ³ ; complex index of refraction, $1.75 - 0.30 i$; size distribution, log-normal with $r_m(\mu m)/\sigma = 0.1/2.0$ for urban fires and $0.05/2.0$ for wildfires and long-term fires	
Baseline smoke injections	
Total smoke emission = 2.25×10^8 tons, 5 percent in the stratosphere	
Urban-suburban fires account for 52 percent of emissions, fire storms for 7 percent, wildfires for 34 percent, and long-term fires for 7 percent	
Total area burned by urban-suburban fires is 2.3×10^5 km ² ; fire storms, 1.2×10^4 km ² ; and wildfires, 5.0×10^5 km ²	

solar energy is deposited above the height at which infrared energy is radiated to space.

Decreases in insolation for several nuclear war scenarios are shown in Fig. 4. The baseline case implies average hemispheric solar fluxes at the ground ≤ 10 percent of normal values for several weeks (apart from any patchiness in the dust and smoke clouds). In addition to causing the temperature declines mentioned above, the attenuated insolation could affect plant growth rates, and vigor in the marine (63), littoral, and terrestrial food chains. In the 10,000-MT "severe" case, average light levels are below the minimum required for photosynthesis for about 40 days over much of the Northern Hemisphere. In a number of other cases, insolation may, for more than 2 months, fall below the compensation point at which photosynthesis is just sufficient to maintain plant metabolism. Because nuclear clouds are likely to remain patchy the first week or two after an exchange, leakage of sunlight through holes in the clouds could enhance plant growth activity above that predicted for average cloud conditions; however, soon thereafter the holes are likely to be sealed.

Sensitivity Tests

A large number of sensitivity calculations were carried out as part of this study (15). The results are summarized here. Reasonable variations in the nuclear dust parameters in the baseline scenario produce initial hemispherically averaged dust optical depths varying from about 0.2 to 3.0. Accordingly, nuclear dust alone could have a major climatic impact. In the baseline case, the dust opacity is much greater than the total aerosol opacity associated with the El Chichón and Agung eruptions (59, 64); even when the dust parameters are assigned their least adverse values within the plausible range, the effects are comparable to those of a major volcanic explosion.

Figure 5 compares nuclear cloud optical depths for several variations of the baseline model smoke parameters (with dust included). In the baseline case, it is assumed that fire storms inject only a small fraction (≈ 5 percent) of the total smoke emission into the stratosphere (65). Thus, case 1 and case 3 (no firestorms) are very similar. As an extreme excursion, all the nuclear smoke is injected into the stratosphere and rapidly dispersed around the globe (case 26); large optical depths can then persist for a year (Fig. 5). Prolongation of optical

effects is also obtained in case 22, where the tropospheric washout lifetime of smoke particles is increased from 10 to 30 days near the ground. By contrast, when the nuclear smoke is initially contained near the ground and dynamical and hydrological removal processes are assumed to be unperturbed, smoke depletion occurs much faster (case 25). But even in this case, some of the smoke still diffuses to the upper troposphere and remains there for several months (66).

In a set of optical calculations, the imaginary refractive index of the smoke was varied between 0.3 and 0.01. The optical depths calculated for indices between 0.1 and 0.3 show virtually no differences (cases 1 and 27 in Fig. 5). At an index of 0.05, the absorption optical depth (52) is reduced by only ≈ 50 percent, and at 0.01, by ≈ 85 percent. The overall opacity (absorption plus scattering), moreover, increases by ≈ 5 per-

cent. These results show that light absorption and heating in nuclear smoke clouds remain high until the graphitic carbon fraction of the smoke falls below a few percent.

One sensitivity test (case 29, not illustrated) considers the optical effects in the Southern Hemisphere (SH) of dust and soot transported from the NH stratosphere. In this calculation, the smoke in the 300-MT SH case 13 is combined with half the baseline stratospheric dust and smoke (to approximate rapid global dispersion in the stratosphere). The initial optical depth is ≈ 1 over the SH, dropping to about 0.3 in 3 months. Predicted average SH continental surface temperatures fall by 8 K within several weeks and remain at least 4 K below normal for nearly 8 months. The seasonal influence should be taken into account, however. For example, the worst consequences for the NH might result from a spring or

Fig. 3. Northern Hemisphere troposphere and stratosphere temperature perturbations (in Kelvins; $1\text{ K} = 1^\circ\text{C}$) after the baseline nuclear exchange (case 1). The hatched area indicates cooling. Ambient pressure levels in millibars are also given.

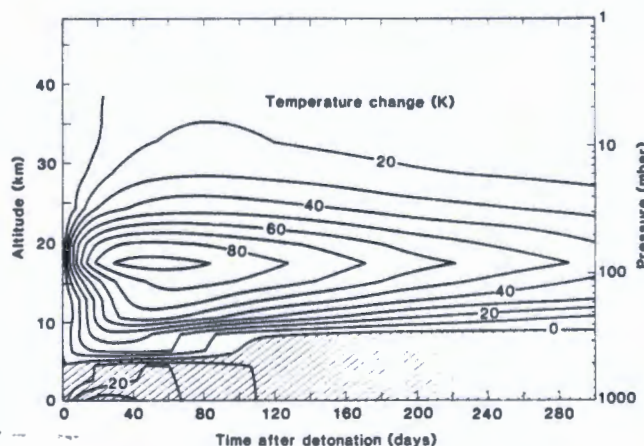
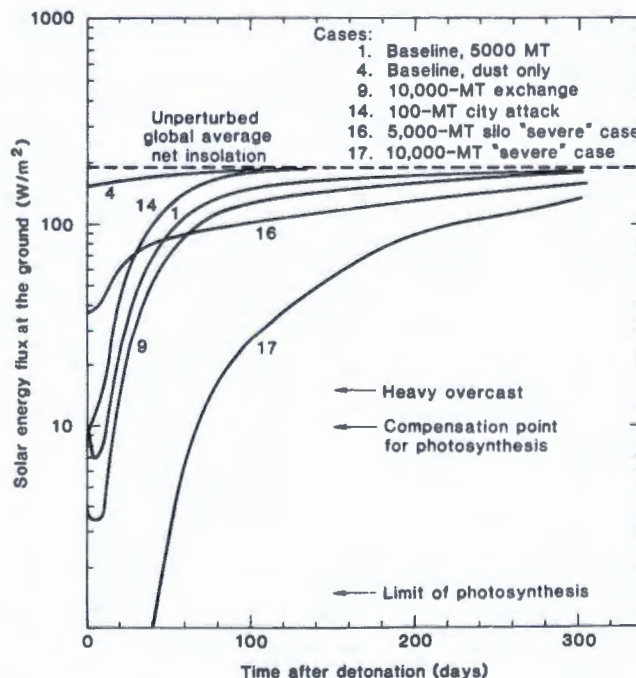


Fig. 4. Solar energy fluxes at the ground over the Northern Hemisphere in the aftermath of a nuclear exchange. Results are given for several of the cases in Table 1. (Note the linear time scale.) Solar fluxes are averaged over the diurnal cycle and over the hemisphere. In cases 4 and 16 fires are neglected. Also indicated are the approximate flux levels at which photosynthesis cannot keep pace with plant respiration (compensation point) and at which photosynthesis ceases. These limits vary for different species.



summer exchange, when crops are vulnerable and fire hazards are greatest. The SH, in its fall or winter, might then be least sensitive to cooling and darkening. Nevertheless, the implications of this scenario for the tropical regions in both hemispheres appear to be serious and worthy of further analysis. Seasonal factors can also modulate the atmospheric response to perturbations by smoke and dust, and should be considered.

A number of sensitivity tests for more severe cases were run with exchange yields ranging from 1000 to 10,000 MT and smoke and dust parameters assigned more adverse, but not implausible, values. The predicted effects are substantially worse (see below). The lower probabilities of these severe cases must be weighed against the catastrophic outcomes which they imply. It would be prudent policy to assess the importance of these scenarios in terms of the product of their probabilities and the costs of their corresponding effects. Unfortu-

nately, we are unable to give an accurate quantitative estimate of the relevant probabilities. By their very nature, however, the severe cases may be the most important to consider in the deployment of nuclear weapons.

With these reservations, we present the optical depths for some of the more severe cases in Fig. 6. Large opacities can persist for a year, and land surface temperatures can fall to 230 to 240 K, about 50 K below normal. Combined with low light levels (Fig. 4), these severe scenarios raise the possibility of widespread and catastrophic ecological consequences.

Two sensitivity tests were run to determine roughly the implications for optical properties of aerosol agglomeration in the early expanding clouds. (The simulations already take into account continuous coagulation of the particles in the dispersed clouds.) Very slow dispersion of the initial stabilized dust and smoke clouds, taking nearly 8 months to cover

the NH, was assumed. Coagulation of particles reduced the average opacity after 3 months by about 40 percent. When the adhesion efficiency of the colliding particles was also maximized, the average opacity after 3 months was reduced by ≈ 75 percent. In the most likely situation, however, prompt agglomeration and coagulation might reduce the average hemispheric cloud optical depths by 20 to 50 percent.

Other Effects

We also considered, in less detail, the long-term effects of radioactive fallout, fireball-generated NO_x , and pyrogenic toxic gases (15). The physics of radioactive fallout is well known (2, 5, 12, 27, 67). Our calculations bear primarily on the widespread intermediate time scale accumulation of fallout due to washout and dry deposition of dispersed nuclear dust (68). To estimate possible exposure

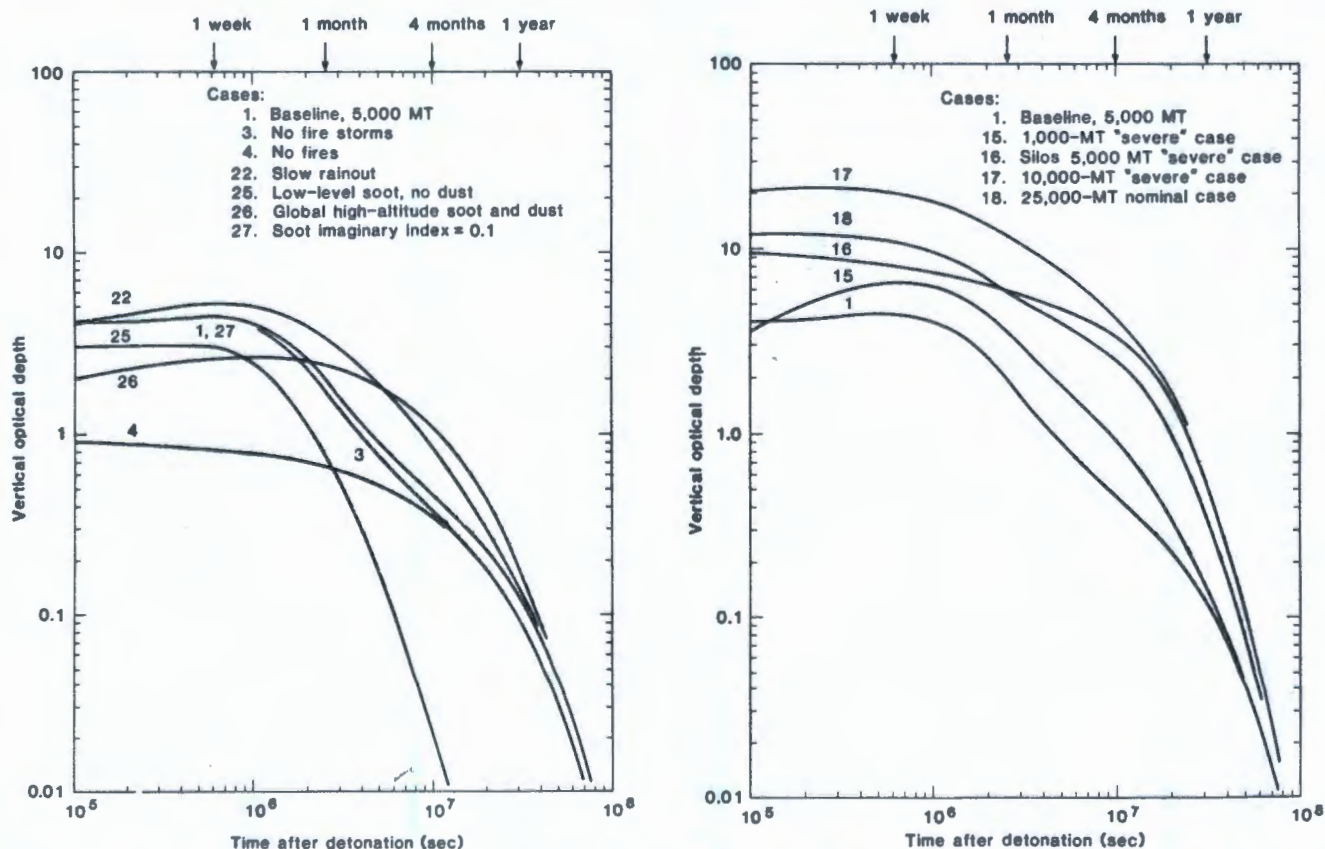


Fig. 5 (left). Time-dependent vertical optical depths (absorption plus scattering at 550 nm) of nuclear clouds, in a sensitivity analysis. Optical depths are average values for the Northern Hemisphere. All cases shown correspond to parameter variations of the baseline model (case 1) and include dust appropriate to it: case 3, no fire storms; case 4, no fires; case 22, smoke rainout rate decreased by a factor of 3; case 25, smoke initially confined to the lowest 3 km of the atmosphere; case 26, smoke initially distributed between 13 and 19 km over the entire globe; and case 27, smoke imaginary part of refractive index reduced from 0.3 to 0.1. For comparison, in case 4, only dust from the baseline model is considered (fires are ignored). Fig. 6 (right). Time-dependent vertical optical depths (absorption plus scattering at 550 nm) for enhanced cases of explosion yield or nuclear dust and smoke production. Conditions are detailed elsewhere (15). Weapon yield inventories are identical to the nominal cases of the same total yield described in Table 1 (cases 16 and 18 are also listed there). The "severe" cases generally include a sixfold increase in fine dust injection and a doubling of smoke emission. In cases 15, 17, and 18, smoke causes most of the opacity during the first 1 to 2 months. In cases 17 and 18, dust makes a major contribution to the optical effects beyond 1 to 2 months. In case 16, fires are neglected and dust from surface bursts produces all of the opacity.

levels, we adopt a fission yield fraction of 0.5, for all weapons. For exposure to only the gamma emission of radioactive dust that begins to fall out after 2 days in the baseline scenario (5000 MT), the hemispherically averaged total dose accumulated by humans over several months could be ≈ 20 rads, assuming no shelter from or weathering of the dust. Fallout during this time would be confined largely to northern mid-latitudes; hence the dose there could be ≈ 2 to 3 times larger (69, 70). Considering ingestion of biologically active radionuclides (27, 71) and occasional exposure to localized fallout, the average total chronic mid-latitude dose of ionizing radiation for the baseline case could be ≈ 50 rads of whole-body external gamma radiation, plus ≈ 50 rads to specific body organs from internal beta and gamma emitters (71, 72). In a 10,000-MT exchange, under the same assumptions, these mean doses would be doubled. Such doses are roughly an order of magnitude larger than previous estimates, which neglected intermediate time scale washout and fallout of tropospheric nuclear debris from low-yield (< 1 -MT) detonations.

The problem of NO_x produced in the fireballs of high-yield explosions, and the resulting depletion of stratospheric ozone, has been treated in a number of studies (2-4, 7, 73). In our baseline case a maximum hemispherically averaged ozone reduction of ≈ 30 percent is found. This would be substantially smaller if individual warhead yields were all reduced below 1 MT. Considering the relation between solar UV-B radiation increases and ozone decreases (74), UV-B doses roughly twice normal are expected in the first year after a baseline exchange (when the dust and soot had dissipated). Large UV-B effects could accompany exchanges involving warheads of greater yield (or large multi-burst laydowns).

A variety of toxic gases (pyrotoxins) would be generated in large quantities by nuclear fires, including CO and HCN. According to Crutzen and Birks (7), heavy air pollution, including elevated ozone concentrations, could blanket the NH for several months. We are also concerned about dioxins and furans, extremely persistent and toxic compounds which are released during the combustion of widely used synthetic organic chemicals (75). Hundreds of tons of dioxins and furans could be generated during a nuclear exchange (76). The long-term ecological consequences of such nuclear pyrotoxins seem worthy of further consideration.

Meteorological Perturbations

Horizontal variations in sunlight absorption in the atmosphere, and at the surface, are the fundamental drivers of atmospheric circulation. For many of the cases considered in this study, sizable changes in the driving forces are implied. For example, temperature contrasts greater than 10 K between NH continental areas and adjacent oceans may induce a strong monsoonal circulation, in some ways analogous to the wintertime pattern near the Indian subcontinent. Similarly, the temperature contrast between debris-laden atmospheric regions and adjacent regions not yet filled by smoke and dust will cause new circulation patterns.

Thick clouds of nuclear dust and smoke can thus cause significant climatic perturbations, and related effects, through a variety of mechanisms: reflection of solar radiation to space and absorption of sunlight in the upper atmosphere, leading to overall surface cooling; modification of solar absorption and heating patterns that drive the atmospheric circulation on small scales (77) and large scales (78); introduction of excess water vapor and cloud condensation nuclei, which affect the formation of clouds and precipitation (79); and alteration of the surface albedo by fires and soot (80). These effects are closely coupled in determining the overall response of the atmosphere to a nuclear war (81). It is not yet possible to forecast in detail the changes in coupled atmospheric circulation and radiation fields, and in weather and microclimates, which would accompany the massive dust and smoke injections treated here. Hence speculation must be limited to the most general considerations.

Water evaporation from the oceans is a continuing source of moisture for the marine boundary layer. A heavy semi-permanent fog or haze layer might blanket large bodies of water. The consequences for marine precipitation are not clear, particularly if normal prevailing winds are greatly modified by the perturbed solar driving force. Some continental zones might be subject to continuous snowfall for several months (10). Precipitation can lead to soot removal, although this process may not be very efficient for nuclear clouds (77, 79). It is likely that, on average, precipitation rates would be generally smaller than in the ambient atmosphere; the major remaining energy source available for storm genesis is the latent heat from ocean evaporation, and the upper atmosphere is warmer than the lower atmo-

sphere which suppresses convection and rainfall.

Despite possible heavy snowfalls, it is unlikely that an ice age would be triggered by a nuclear war. The period of cooling (≈ 1 year) is probably too short to overcome the considerable inertia in the earth's climate system. The oceanic heat reservoir would probably force the climate toward contemporary norms in the years after a war. The CO_2 input from nuclear fires is not significant climatologically (7).

Interhemispheric Transport

In earlier studies it was assumed that significant interhemispheric transport of nuclear debris and radioactivity requires a year or more (2). This was based on observations of transport under ambient conditions, including dispersion of debris clouds from individual atmospheric nuclear weapons tests. However, with dense clouds of dust and smoke produced by thousands of nearly simultaneous explosions, large dynamical disturbances would be expected in the aftermath of a nuclear war. A rough analogy can be drawn with the evolution of global-scale dust storms on Mars. The lower martian atmosphere is similar in density to the earth's stratosphere, and the period of rotation is almost identical to the earth's (although the solar insolation is only half the terrestrial value). Dust storms that develop in one hemisphere on Mars often rapidly intensify and spread over the entire planet, crossing the equator in a mean time of ≈ 10 days (15, 82, 83). The explanation apparently lies in the heating of the dust aloft, which then dominates other heat sources and drives the circulation. Haberle *et al.* (82) used a two-dimensional model to simulate the evolution of martian dust storms and found that dust at low latitudes, in the core of the Hadley circulation, is the most important in modifying the winds. In a nuclear exchange, most of the dust and smoke would be injected at middle latitudes. However, Haberle *et al.* (82) could not treat planetary-scale waves in their calculations. Perturbations of planetary wave amplitudes may be critical in the transport of nuclear war debris between middle and low latitudes.

Significant atmospheric effects in the SH could be produced (i) through dust and smoke injection resulting from explosions on SH targets, (ii) through transport of NH debris across the meteorological equator by monsoon-like winds (84), and (iii) through interhemispheric transport in the upper tropo-

sphere and stratosphere, driven by solar heating of nuclear dust and smoke clouds. Photometric observations of the El Chichón volcanic eruption cloud (origin, 14°N) by the Solar Mesosphere Explorer satellite show that 10 to 20 percent of the stratospheric aerosol had been transported to the SH after ≈ 7 weeks (85).

Discussion and Conclusions

The studies outlined here suggest severe long-term climatic effects from a 5000-MT nuclear exchange. Despite uncertainties in the amounts and properties of the dust and smoke produced by nuclear detonations, and the limitations of models available for analysis, the following tentative conclusions may be drawn.

1) Unlike most earlier studies [for instance, (2)], we find that a global nuclear war could have a major impact on climate—manifested by significant surface darkening over many weeks, subfreezing land temperatures persisting for up to several months, large perturbations in global circulation patterns, and dramatic changes in local weather and precipitation rates—a harsh “nuclear winter” in any season. Greatly accelerated inter-hemispheric transport of nuclear debris in the stratosphere might also occur, although modeling studies are needed to quantify this effect. With rapid inter-hemispheric mixing, the SH could be subjected to large injections of nuclear debris soon after an exchange in the Northern Hemisphere. In the past, SH effects have been assumed to be minor. Although the climate disturbances are expected to last more than a year, it seems unlikely that a major long-term climatic change, such as an ice age, would be triggered.

2) Relatively large climatic effects could result even from relatively small nuclear exchanges (100 to 1000 MT) if urban areas were heavily targeted, because as little as 100 MT is sufficient to devastate and burn several hundred of the world's major urban centers. Such a low threshold yield for massive smoke emissions, although scenario-dependent, implies that even limited nuclear exchanges could trigger severe aftereffects. It is much less likely that a 5000- to 10,000-MT exchange would have only minor effects.

3) The climatic impact of sooty smoke from nuclear fires ignited by airbursts is expected to be more important than that of dust raised by surface bursts (when both effects occur). Smoke absorbs sunlight efficiently, whereas soil dust is gen-

erally nonabsorbing. Smoke particles are extremely small (typically $< 1 \mu\text{m}$ in radius), which lengthens their atmospheric residence time. There is also a high probability that nuclear explosions over cities, forests, and grasslands will ignite widespread fires, even in attacks limited to missile silos and other strategic military targets.

4) Smoke from urban fires may be more important than smoke from collateral forest fires for at least two reasons: (i) in a full-scale exchange, cities holding large stores of combustible materials are likely to be attacked directly; and (ii) intense fire storms could pump smoke into the stratosphere, where the residence time is a year or more.

5) Nuclear dust can also contribute to the climatic impact of a nuclear exchange. The dust-climate effect is very sensitive to the conduct of the war; a smaller effect is expected when lower yield weapons are deployed and airbursts dominate surface land bursts. Multiburst phenomena might enhance the climatic effects of nuclear dust, but not enough data are available to assess this issue.

6) Exposure to radioactive fallout may be more intense and widespread than predicted by empirical exposure models, which neglect intermediate fallout extending over many days and weeks, particularly when unprecedented quantities of fission debris are released abruptly into the troposphere by explosions with submegaton yields. Average NH mid-latitude whole-body gamma-ray doses of up to 50 rads are possible in a 5000-MT exchange; larger doses would accrue within the fallout plumes of radioactive debris extending hundreds of kilometers downwind of targets. These estimates neglect a probably significant internal radiation dose due to biologically active radionuclides.

7) Synergisms between long-term nuclear war stresses—such as low light levels, subfreezing temperatures, exposure to intermediate time scale radioactive fallout, heavy pyrogenic air pollution, and UV-B flux enhancements—aggravated by the destruction of medical facilities, food stores, and civil services, could lead to many additional fatalities, and could place severe stresses on the global ecosystem. An assessment of the possible long-term biological consequences of the nuclear war effects quantified in this study is made by Ehrlich *et al.* (86).

Our estimates of the physical and chemical impacts of nuclear war are necessarily uncertain because we have used one-dimensional models, because the

data base is incomplete, and because the problem is not amenable to experimental investigation. We are also unable to forecast the detailed nature of the changes in atmospheric dynamics and meteorology implied by our nuclear war scenarios, or the effect of such changes on the maintenance or dispersal of the initiating dust and smoke clouds. Nevertheless, the magnitudes of the first-order effects are so large, and the implications so serious, that we hope the scientific issues raised here will be vigorously and critically examined.

References and Notes

1. J. Hampson, *Nature (London)* **250**, 189 (1974).
2. National Academy of Sciences, *Long-Term Worldwide Effects of Multiple Nuclear-Weapon Detonations* (Washington, D.C., 1975).
3. R. C. Whitten, W. J. Borucki, R. P. Turco, *Nature (London)* **257**, 38 (1975).
4. M. C. MacCracken and J. S. Chang, Eds., *Lawrence Livermore Lab. Rep. UCRL-51653* (1975).
5. J. C. Mark, *Annu. Rev. Nucl. Sci.* **26**, 51 (1976).
6. K. N. Lewis, *Sci. Am.* **241**, 35 (July 1979).
7. P. J. Crutzen and J. W. Birks, *Ambio* **11**, 114 (1982).
8. L. W. Alvarez, W. Alvarez, F. Asaro, H. V. Michel, *Science* **208**, 1095 (1980); W. Alvarez, F. Asaro, H. V. Michel, L. W. Alvarez, *ibid.* **216**, 886 (1982); W. Alvarez, L. W. Alvarez, F. Asaro, H. V. Michel, *Geol. Soc. Am. Spec. Pap.* **190** (1982), p. 305.
9. R. Ganapathy, *Science* **216**, 885 (1982).
10. O. B. Toon *et al.*, *Geol. Soc. Am. Spec. Pap.* **190** (1982), p. 187; J. B. Pollack, O. B. Toon, T. P. Ackerman, C. P. McKay, R. P. Turco, *Science* **219**, 287 (1983).
11. Under the sponsorship of the Defense Nuclear Agency, the National Research Council (NRC) of the National Academy of Sciences has also undertaken a full reassessment of the possible climatic effects of nuclear war. The present analysis was stimulated, in part, by earlier NRC interest in a preliminary estimate of the climatic effects of nuclear dust.
12. Office of Technology Assessment, *The Effects of Nuclear War* (OTA-NS-89, Washington, D.C., 1979).
13. J. E. Cogle and P. J. Lindop, *Ambio* **11**, 106 (1982).
14. S. Bergstrom *et al.*, “Effects of nuclear war on health and health services,” *WHO Publ.* **A36.12** (1983).
15. R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, C. Sagan, in preparation.
16. R. P. Turco, P. Hamill, O. B. Toon, R. C. Whitten, C. S. Kiang, *J. Atmos. Sci.* **36**, 699 (1979); *NASA Tech. Rep.* **1362** (1979); R. P. Turco, O. B. Toon, P. Hamill, R. C. Whitten, *J. Geophys. Res.* **86**, 1113 (1981); R. P. Turco, O. B. Toon, R. C. Whitten, *Rev. Geophys. Space Phys.* **20**, 233 (1982); R. P. Turco, O. B. Toon, R. C. Whitten, P. Hamill, R. G. Keese, *J. Geophys. Res.* **88**, 5299 (1983).
17. O. B. Toon, R. P. Turco, P. Hamill, C. S. Kiang, R. C. Whitten, *J. Atmos. Sci.* **36**, 718 (1979); *NASA Tech. Rep.* **1363** (1979).
18. O. B. Toon and T. P. Ackerman, *Appl. Opt.* **20**, 3657 (1981); T. P. Ackerman and O. B. Toon, *ibid.*, p. 3661; J. N. Cuzzi, T. P. Ackerman, L. C. Helme, *J. Atmos. Sci.* **39**, 917 (1982).
19. Prediction of circulation anomalies and attendant changes in regional weather patterns requires an appropriately designed three-dimensional general circulation model with at least the following features: horizontal resolution of 10° or better, high vertical resolution through the troposphere and stratosphere, cloud and precipitation parameterizations that allow for excursions well outside present-day experience, ability to transport dust and smoke particles, an interactive radiative transport scheme to calculate dust and smoke effects on light fluxes and heating rates, allowance for changes in particle sizes with time and for wet and dry deposition, and possibly a treatment of the coupling between surface winds and ocean currents and temperatures. Even if such a model were available today, it would not be able to resolve questions of patchiness on horizontal scales of less than several hundred kilometers, of local-

- sphere. The residence time of fine particles in the stratosphere is considerably longer than in the upper troposphere because of the greater stability of the stratospheric air layers and the absence of precipitation in the stratosphere. With large smoke injections, however, the ambient temperature profile would be substantially distorted (for instance, see Fig. 3) and a "stratosphere" might form in the vicinity of the smoke cloud, increasing its residence time at all altitudes (15). Thus the duration of sunlight attenuation and temperature perturbations in Figs. 1 to 6 may be considerably underestimated.
66. Transport of soot from the boundary layer into the overlying free troposphere can occur by diurnal expansion and contraction of the boundary layer, by large-scale advection, and by strong localized convection.
 67. F. Barnaby and J. Rotblat, *Ambio* 11, 84 (1982).
 68. The term "intermediate" fallout distinguishes the radioactivity deposited between several days and ~1 month after an exchange from "prompt" fallout (≤ 1 day) and "late" fallout (months to years). Intermediate fallout is expected to be at least hemispheric in scale and can still deliver a significant chronic whole-body gamma-ray dose. It may also contribute a substantial internal dose, for example, from ^{131}I . The intermediate time scale gamma-ray dose represents, in one sense, the minimum average exposure far from targets and plumes of prompt fallout. However, the geographic distribution of intermediate fallout would still be highly variable, and estimates of the average dose made with a one-dimensional model are greatly idealized. The present calculations were calibrated against the observed prompt fallout of nuclear test explosions (15).
 69. There is also reason to believe that the fission yield fraction of nuclear devices may be increasing as warhead yields decrease and uranium processing technology improves. If the fission fraction were unity, our dose estimates would have to be doubled. We also neglect additional potential sources of radioactive fallout from salted "dirty" weapons and explosions over nuclear reactors and fuel reprocessing plants.
 70. J. Knox (Lawrence Livermore Lab. Rep. UCRL-89907, in press) reports fallout calculations which explicitly account for horizontal spreading and transport of nuclear debris clouds. For a 5300-MT strategic exchange, Knox computes average whole-body gamma-ray doses of 20 rads from 40° to 60°N , with smaller average doses elsewhere. Hot spots of up to 200 rads over areas of $\sim 10^6 \text{ km}^2$ are also predicted for intermediate time scale fallout. These calculations are consistent with our estimates.
 71. H. Lee and W. E. Strobe [Stanford Res. Inst. Rep. EGU 2981 (1974)] studied U.S. exposure to transoceanic fallout generated by several assumed Sino-Soviet nuclear exchanges. Taking into account weathering of fallout debris, protection by shelters, and a 5-day delay before initial exposure, potential whole-body gamma-ray doses ≤ 10 rads and internal doses ≥ 10 to 100 rads, mainly to the thyroid and intestines, were estimated.
 72. These estimates assume normal rates and patterns of precipitation, which control the intermediate time scale radioactive fallout. In severely perturbed cases, however, it may happen that the initial dispersal of the airborne radioactivity is accelerated by heating, but that intermediate time scale deposition is suppressed by lack of precipitation over land.
 73. H. Johnston, G. Whitten, J. Birks, *J. Geophys. Res.* 78, 6107 (1973); H. S. Johnston, *ibid.* 82, 3119 (1977).
 74. S. A. W. Gerstl, A. Zardecki, H. L. Wiser, *Nature (London)* 294, 352 (1981).
 75. M. P. Esposito, T. O. Tiernan, F. E. Dryden, *U.S. EPA Rep. EPA-600/280-197* (1980).
 76. J. Josephson, *Environ. Sci. Technol.* 17, 124A (1983). In burning of PCB's, for example, release of toxic polycyclic chlorinated organic compounds can amount to 0.1 percent by weight. In the United States more than 300,000 tons of PCB's are currently in use in electrical systems [S. Miller, *Environ. Sci. Technol.* 17, 11A (1983)].
 77. C.-S. Chen and H. D. Orville [*J. Appl. Meteorol.* 16, 401 (1977)] model the effects of fine graphitic dust on cumulus-scale convection. They show that strong convective motions can be established in still air within 10 minutes after the injection of a kilometer-sized cloud of sub-micrometer particles of carbon black, at mixing ratios ≤ 50 ppb by mass. Addition of excess humidity in their model to induce rainfall results in still stronger convection; the carbon dust is raised higher and spread farther horizontally, while ≈ 20 percent is scavenged by the precipitation. W. M. Gray, W. M. Frank, M. L. Corrin, and C. A. Stokes [*J. Appl. Meteorol.* 15, 355 (1976)] discuss possible mesoscale ($\geq 100 \text{ km}$) weather modifications due to large carbon dust injections.
 78. C. Covey, S. Schneider, and S. Thompson (in preparation) report GCM simulations which include soot burdens similar to those in our baseline case. They find major perturbations in the global circulation within a week of injection, with strong indications that some of the nuclear debris at northern mid-latitudes would be transported upward and toward the equator.
 79. R. C. Eagan, P. V. Hobbs, L. F. Radke, *J. Appl. Meteorol.* 13, 553 (1974).
 80. C. Sagan, O. B. Toon, and J. B. Pollack [*Science* 206, 1363 (1979)] discuss the impact of anthropogenic albedo changes on global climate. Nuclear war may cause albedo changes by burning large areas of forest and grassland; by generating massive quantities of soot which can settle out on plants, snowfields, and ocean surface waters; and by altering the pattern and extent of ambient water clouds. The nuclear fires in the baseline case consume an area $\approx 7.5 \times 10^6 \text{ km}^2$, or only ≈ 0.5 percent of the global landmass; it is doubtful that an albedo variation over such a limited area is significant. All the soot in the baseline nuclear war case, if spread uniformly over the earth, would amount to a layer $\sim 0.5 \mu\text{m}$ thick. Even if the soot settled out uniformly on all surfaces, the first rainfall would wash it into soils and watersheds. The question of the effect of soot on snow and ice fields is under debate (J. Birks, private communication). In general, soot or sand accelerates the melting of snow and ice. Soot that settles in the oceans would be rapidly removed by nonselective filter-feeding plankton, if these survived the initial darkness and ionizing radiation.
 81. In the present calculations, chemical changes in stratospheric O_3 and NO_2 concentrations cause a small average temperature perturbation compared to that caused by nuclear dust and smoke; it seems unlikely that chemically induced climatic disturbances would be a major factor in a nuclear war. Tropospheric ozone concentrations, if tripled (7), would lead to a small greenhouse warming of the surface [W. C. Wang, Y. L. Yung, A. A. Lacis, T. Mo, J. E. Hansen, *Science* 194, 685 (1976)]. This might result in more rapid surface temperature recovery. However, the tropospheric O_3 increase is transient (~ 3 months in duration) and probably secondary in importance to the contemporaneous smoke and dust perturbations.
 82. R. M. Haberle, C. B. Leovy, J. B. Pollack, *Icarus* 50, 322 (1983).
 83. During the martian dust storm of 1971-1972, the IRIS experiment on Mariner 9 observed that suspended particles heated the atmosphere and produced a vertical temperature gradient that was substantially subadiabatic [R. B. Hanel *et al.*, *Icarus* 17, 423 (1972); J. B. Pollack *et al.*, *J. Geophys. Res.* 84, 2929 (1979)].
 84. V. V. Alexandrov, private communication; S. H. Schneider, private communication.
 85. G. E. Thomas, B. M. Jakosky, R. A. West, R. W. Sanders, *Geophys. Res. Lett.* 10, 997 (1983); J. B. Pollack *et al.*, *ibid.*, p. 989; B. M. Jakosky, private communication.
 86. P. Ehrlich *et al.*, *Science* 222, 1293 (1983).
 87. H. M. Foley and M. A. Ruderman, *J. Geophys. Res.* 78, 4441 (1973).
 88. We gratefully acknowledge helpful discussions with J. Berry, H. A. Bethe, C. Billings, J. Birks, H. Brode, R. Cicerone, L. Colin, P. Crutzen, R. Decker, P. J. Dolan, P. Dyal, F. J. Dyson, P. Ehrlich, B. T. Feld, R. L. Garwin, F. Gilmore, L. Grinspoon, M. Grover, J. Knox, A. Kuhl, C. Leovy, M. MacCracken, J. Mahlman, J. Marcum, P. Morrison, E. Patterson, R. Perret, G. Rawson, J. Rotblat, E. E. Salpeter, S. Soter, R. Speed, E. Teller, and R. Whitten on a variety of subjects related to this work. S. H. Schneider, C. Covey, and S. Thompson of the National Center for Atmospheric Research generously shared with us preliminary GCM calculations of the global weather effects implied by our smoke emissions. We also thank the almost 100 participants of a 5-day symposium held in Cambridge, Mass., 22 to 26 April, for reviewing our results; that symposium was organized by the Conference on the Longterm Worldwide Biological Consequences of Nuclear War under a grant from the W. Alton Jones Foundation. Special thanks go to Janet M. Tollas for compiling information on world urbanization, to May Liu for assistance with computer programming, and to Mary Maki for diligence in preparing the manuscript.

- ized perturbations in boundary-layer dynamics, or of mesoscale dispersion and removal of dust and smoke clouds.
20. Advisors, *Ambio* 11, 94 (1982).
 21. R. T. Pretty, Ed., *Jane's Weapon Systems, 1982-1983* (Jane's, London, 1982).
 22. *The Military Balance 1982-1983* (International Institute for Strategic Studies, London, 1982).
 23. *World Armaments and Disarmament*, Stockholm International Peace Research Institute Yearbook 1982 (Taylor & Francis, London, 1982).
 24. R. Forsberg, *Sci. Am.* 247, 52 (November 1982).
 25. The unprecedented difficulties involved in controlling a limited nuclear exchange are discussed by, for example, P. Bracken and M. Shubik [*Technol. Soc.* 4, 155 (1982)] and by D. Ball [*Adelphi Paper 169* (International Institute for Strategic Studies, London, 1981)].
 26. G. Kemp, *Adelphi Paper 106* (International Institute for Strategic Studies, London, 1974).
 27. S. Glasstone and P. J. Dolan, Eds., *The Effects of Nuclear Weapons* (Department of Defense, Washington, D.C., 1977).
 28. The areas cited are subject to peak overpressures ≥ 10 to 20 cal/cm^2 .
 29. A 1-MT surface explosion ejects $\sim 5 \times 10^6$ tons of debris, forming a large crater (27). Typical soils consist of ~ 5 to 25 percent by weight of grains $\leq 1 \mu\text{m}$ in radius [G. A. D'Almeida and L. Schutz, *J. Climate Appl. Meteorol.* 22, 233 (1983); G. Rawson, private communication]. However, the extent of disaggregation of the soil into parent grain sizes is probably ≤ 10 percent [R. G. Pinnick, G. Fernandez, B. D. Hinds, *Appl. Opt.* 22, 95 (1983)] and would depend in part on soil moisture and compaction.
 30. A 1-MT surface explosion vaporizes $\sim 2 \times 10^6$ to 4×10^6 tons of soil (27), which is ingested by the fireball. Some silicates and other refractory materials later renucleate into fine glassy spheres [M. W. Nathans, R. Thews, I. J. Russell, *Adv. Chem. Ser.* 93, 360 (1970)].
 31. A 1-MT surface explosion raises significant quantities of dust over an area of $\approx 100 \text{ km}^2$ by "popcorning," due to thermal radiation, and by saltation, due to pressure winds and turbulence (27). Much of the dust is sucked up by the afterwinds behind the rising fireball. Size sorting should favor greatest lifting for the finest particles. The quantity of dust lofted would be sensitive to soil type, moisture, compaction, vegetation cover, and terrain. Probably $> 1 \times 10^6$ tons of dust per megaton can be incorporated into the stabilized clouds in this manner.
 32. R. G. Gutmacher, G. H. Higgins, H. A. Tewes, *Lawrence Livermore Lab. Rep. UCRL-14397* (1983); J. Carpenter, private communication.
 33. M. W. Nathans, R. Thews, I. J. Russell [in (30)]. These data suggest number size distributions that are log-normal at small sizes ($\leq 3 \mu\text{m}$) and power law ($r^{-\alpha}$) at larger sizes. Considering data from a number of nuclear tests, we adopted an average log-normal mode radius of $0.25 \mu\text{m}$, $\sigma = 2.0$, and an exponent, $\alpha = 4$ (15). If all particles in the stabilized clouds have radii in the range 0.01 to $1000 \mu\text{m}$, the adopted size distribution has ≈ 8 percent of the total mass in particles $\leq 1 \mu\text{m}$ in radius; this fraction of the stabilized cloud mass represents ≈ 0.5 percent of the total ejecta and sweep-up mass of a surface explosion and amounts to ≈ 25 tons per kiloton of yield.
 34. Atmospheric dust from volcanic explosions differs in several important respects from that produced by nuclear explosions. A volcanic eruption represents a localized dust source, while a nuclear war would involve thousands of widely distributed sources. The dust mass concentration in stabilized nuclear explosion clouds is low ($\leq 1 \text{ g/m}^3$), while volcanic eruption columns are so dense they generally collapse under their own weight [G. P. L. Walker, *J. Volcanol. Geotherm. Res.* 11, 81 (1981)]. In the dense volcanic clouds particle agglomeration, particularly under the influence of electrical charge, can lead to accelerated removal by sedimentation [S. N. Carey and H. Sigurdsson, *J. Geophys. Res.* 87, 7061 (1982); S. Brazier et al., *Nature (London)* 301 115 (1983)]. The size distribution of volcanic ash is also fundamentally different from that of nuclear dust [W. I. Rose et al., *Am. J. Sci.* 280, 671 (1980)], because the origins of the particles are so different. The injection efficiency of nuclear dust into the stratosphere by megaton-yield explosions is close to unity, while the injection efficiency of fine volcanic dust appears to be very low (15). For these reasons and others, the observed climatic effects of major historical volcanic eruptions cannot be used, as in (2), to calibrate the potential climatic effect of nuclear dust merely by scaling energy or soil volume. However, in cases where the total amount of submicrometer volcanic material that remained in the stratosphere could be determined, climate models have been applied and tested [J. B. Pollack et al., *J. Geophys. Res.* 81, 1071 (1976)]. We used such a model in this study to predict the effects of specific nuclear dust injections.
 35. E. Ishikawa and D. L. Swain, Translators, *Hiroshima and Nagasaki: The Physical, Medical and Social Effects of the Atomic Bombings* (Basic Books, New York, 1981).
 36. At Hiroshima, a weapon of roughly 13 KT created a fire over $\approx 13 \text{ km}^2$. At Nagasaki, where irregular terrain inhibited widespread fire ignition, a weapon of roughly 22 KT caused a fire over $\approx 7 \text{ km}^2$. These two cases suggest that low-yield (≤ 1 -MT) nuclear explosions can readily ignite fires over an area of ≈ 0.3 to $1.0 \text{ km}^2/\text{KT}$ —roughly the area contained within the $\approx 10 \text{ cal/cm}^2$ and the $\approx 2 \text{ psi}$ overpressure contours (27).
 37. A. Broido, *Bull. At. Sci.* 16, 409 (1960).
 38. C. F. Miller, "Preliminary evaluation of fire hazards from nuclear detonations," *SRI (Stanford Res. Inst.) Memo. Rep. Project IMU-4021-302* (1962).
 39. R. U. Ayers, *Environmental Effects of Nuclear Weapons (HI-518-RR)*, Hudson Institute, New York, 1965, vol. 1.
 40. S. B. Martin, "The role of fire in nuclear warfare," *United Research Services Rep. URS-764 (DNA 2692F)* (1974).
 41. *DCPA Attack Environment Manual* (Department of Defense, Washington, D.C., 1973), chapter 3.
 42. *FEMA Attack Environment Manual (CPG 2-1A3)*, Federal Emergency Management Agency, Washington, D.C., 1982, chapter 3.
 43. H. L. Brode, "Large-scale urban fires," *Pacific Sierra Res. Corp. Note 348* (1980).
 44. D. A. Larson and R. D. Small, "Analysis of the large urban fire environment," *Pacific Sierra Res. Corp. Rep. 1210* (1982).
 45. Urban and suburban areas of cities with populations exceeding 100,000 (about 2300 worldwide) are surveyed in (15). Also discussed are global reserves of flammable substances, which are shown to be roughly consistent with known rates of production and accumulation of combustible materials. P. J. Crutzen and I. E. Galbally (in preparation) reach similar conclusions about global stockpiles of combustibles.
 46. Smoke emission data for forest fires are reviewed by D. V. Sandberg, J. M. Pierovich, D. G. Fox, and E. W. Ross ["Effects of fire on air," *U.S. Forest Serv. Tech. Rep. WO-9* (1979)]. Largest emission factors occur in intense large-scale fires where smoldering and flaming exist simultaneously, and the oxygen supply may be limited over part of the burning zone. Smoke emissions from synthetic organic compounds would generally be larger than those from forest fuels [C. P. Bankston, B. T. Zinn, R. F. Browner, E. A. Powell, *Combust. Flame* 41, 273 (1981)].
 47. Sooty smoke is a complex mixture of oils, tars, and graphitic (or elemental) carbon. Measured benzene-soluble mass fractions of wildfire smokes fall in the range ≈ 40 to 75 percent [D. V. Sandberg et al. in (46)]. Most of the residue is likely to be brown to black (the color of smoke ranges from white, when large amounts of water vapor are present, to yellow or brown, when oils predominate, to gray or black, when elemental carbon is a major component).
 48. A. Tewarson, in *Flame Retardant Polymeric Material*, M. Lewin, S. M. Atlas, E. M. Pierce, Eds. (Plenum, New York, 1982), vol. 3, pp. 97-153. In small laboratory burns of a variety of synthetic organic compounds, emissions of "solid" materials (which remained on collection filters after baking at 100°C for 24 hours) ranged from ≈ 1 to 15 percent by weight of the carbon consumed; of low-volatility liquids, ≈ 2 to 35 percent; and of high-volatility liquids, ≈ 1 to 40 percent. Optical extinction of the smoke generated by a large number of samples varied from ≈ 0.1 to 1.5 m^2 per gram of fuel burned.
 49. In wildfires, the particle number mode radius is typically about $0.05 \mu\text{m}$ [D. V. Sandberg et al. in (46)]. For burning synthetics the number mode radius can be substantially greater, but a reasonable average value is $0.1 \mu\text{m}$ [C. P. Bankston et al. in (46)]. Often, larger debris particles and firebrands are swept up by powerful fire winds, but they have short atmospheric residence times and are not included in the present estimates (C. K. McMahon and P. W. Ryan, paper presented at the 69th Annual Meeting, Air Pollution Control Association, Portland, Ore., 27 June to 1 July 1976). Nevertheless, because winds exceeding 100 km/hour may be generated in large-scale fires, significant quantities of fine noncombustible surface dust and explosion debris (such as pulverized plaster) might be lifted in addition to the smoke particles.
 50. This assumes an average graphitic carbon mass fraction of about 30 to 50 percent, for a pure carbon imaginary refractive index of 0.6 to 1.0 [J. T. Twitty and J. A. Weinman, *J. Appl. Meteorol.* 10, 725 (1971); S. Chippett and W. A. Gray, *Combust. Flame* 31, 149 (1978)]. The real part of the refractive index of pure carbon is 1.75 , and for many oils is 1.5 to 1.6 . Smoke particles were assigned an average density of 1 g/cm^3 (C. K. McMahon, paper presented at the 76th Annual Meeting, Air Pollution Control Association, Atlanta, Ga., 19 to 24 June 1983). Solid graphite has a density $\approx 2.5 \text{ g/cm}^3$, and most oils, $\approx 1 \text{ g/cm}^3$.
 51. A number of targets with military, economic, or political significance can also be identified in tropical northern latitudes and in the SH (20).
 52. Attenuation of direct sunlight by dust and smoke particles obeys the law $I/I_0 = \exp(-\tau/\mu_0)$, where τ is the total extinction optical depth due to photon scattering and absorption by the particles and μ_0 is the cosine of the solar zenith angle. The optical depth depends on the wavelength of the light and the size distribution and composition of the particles, and is generally calculated from Mie theory (assuming equivalent spherical particles). The total light intensity at the ground consists of a direct component and a diffuse, or scattered, component, the latter usually calculated with a radiative transfer model. The extinction optical depth can be written as $\tau = XML$, where X is the specific cross section (m^2/g particulate), M the suspended particle mass concentration (g/m^3), and L the path length (m). It is the sum of a scattering and an absorption optical depth ($\tau = \tau_s + \tau_a$). Fine dust and smoke particles have scattering coefficients $X_s \approx 3$ to $5 \text{ m}^2/\text{g}$ at visible wavelengths. However, the absorption coefficients X_a are very sensitive to the imaginary part of the index of refraction. For typical soil particles, $X_a \approx 0.1 \text{ m}^2/\text{g}$. For smokes, X_a can vary from ≈ 0.1 to $10 \text{ m}^2/\text{g}$, roughly in proportion to the volume fraction of graphite in the particles. Occasionally, specific extinction coefficients for smoke are given relative to the mass of fuel burned; then X implicitly includes a multiplicative emission factor (grams of smoke generated per gram of fuel burned).
 53. R. P. Turco, O. B. Toon, R. C. Whitten, P. Hamill, *Eos* 63, 901 (1982).
 54. J. A. Ogren, in *Particulate Carbon: Atmospheric Life Cycle*, G. T. Wolff and R. L. Klimisch, Eds. (Plenum, New York, 1982), pp. 379-391.
 55. To estimate the wildfire area, we assume that 25 percent of the total nonurban yield, or 1000 MT , ignites fires over an area of $500 \text{ km}^2/\text{MT}$ —approximately the zone irradiated by 10 cal/cm^2 —and that the fires do not spread outside this zone (39). R. E. Huschke [*Rand Corp. Rep. RM-5073-TAB* (1966)] analyzed the simultaneous flammability of wildland fuels in the United States, and determined that about 50 percent of all fuels are at least moderately flammable throughout the summer months. Because ≈ 50 percent of the land areas of the countries likely to be involved in a nuclear exchange are covered by forest and brush, which are flammable about 50 percent of the time, the 1000-MT ignition yield follows statistically.
 56. Most of the background smoke is injected into the lowest 1 to 2 km of the atmosphere, where it has a short lifetime, and consists on the average of ≈ 10 percent graphitic carbon [R. P. Turco, O. B. Toon, R. C. Whitten, J. B. Pollack, P. Hamill, in *Precipitation Scavenging, Dry Deposition and Resuspension*, H. R. Pruppacher, R. G. Semonin, W. G. N. Slinn, Eds. (Elsevier, New York, 1983), p. 1337]. Thus, the average optical depth of ambient atmospheric soot is only ≈ 1 percent of the initial optical depth of the baseline nuclear war smoke pall.
 57. H. E. Landsberg and J. M. Albert, *Weatherwise* 27, 63 (1974).
 58. H. Stommel and E. Stommel, *Sci. Am.* 240, 176 (June 1979).
 59. O. B. Toon and J. B. Pollack, *Nat. Hist.* 86, 8 (January 1977).
 60. H. H. Lamb, *Climate Present, Past and Future* (Methuen, London, 1977), vols. 1 and 2.
 61. Notwithstanding possible alterations in the surface albedo due to the fires and deposition of soot (15, 80).
 62. S. G. H. Philander, *Nature (London)* 302, 295 (1983); B. C. Weare, *Science* 221, 947 (1983).
 63. D. H. Milne and C. P. McKay, *Geol. Soc. Am. Spec. Pap.* 190 (1982), p. 297.
 64. O. B. Toon, *Eos* 63, 901 (1982).
 65. The stratosphere is normally defined as the region of constant or increasing temperature with increasing height lying just above the tropo-

Long-Term Biological Consequences of Nuclear War

Paul R. Ehrlich, John Harte, Mark A. Harwell, Peter H. Raven
Carl Sagan, George M. Woodwell, Joseph Berry
Edward S. Ayensu, Anne H. Ehrlich, Thomas Eisner
Stephen J. Gould, Herbert D. Grover
Rafael Herrera, Robert M. May, Ernst Mayr
Christopher P. McKay, Harold A. Mooney, Norman Myers
David Pimentel, John M. Teal

Recent studies of large-scale nuclear war (5000- to 10,000-MT yields) have estimated that there would be 750 million immediate deaths from blast alone (1); a total of about 1.1 billion deaths from the combined effects of blast, fire, and radiation (2); and approximately an additional 1.1 billion injuries requiring medical attention (1, 2). Thus, 30 to 50 percent of the total human population could be immediate casualties of a nuclear war. The vast majority of the casualties would be in the Northern Hemisphere, especially in the United States, the U.S.S.R., Europe, and Japan. These enormous numbers have typically been taken to define the full potential catastrophe of such a war. New evidence presented here, however, suggests that the longer term biological effects resulting from climatic changes may be at least as serious as the immediate ones. Our concern in this article is with the 2 billion to 3 billion people not killed immediately, including those in nations far removed from the nuclear conflict.

We consider primarily the results of a nuclear war in which sufficient dust and soot are injected into the atmosphere to attenuate most incident solar radiation, a

possibility first suggested by Ehrlich *et al.* (3), and first shown quantitatively and brought to wide attention by Crutzen and Birks (1). In a wide range of nuclear exchange scenarios, with yields from 100

Summary. Subfreezing temperatures, low light levels, and high doses of ionizing and ultraviolet radiation extending for many months after a large-scale nuclear war could destroy the biological support systems of civilization, at least in the Northern Hemisphere. Productivity in natural and agricultural ecosystems could be severely restricted for a year or more. Postwar survivors would face starvation as well as freezing conditions in the dark and be exposed to near-lethal doses of radiation. If, as now seems possible, the Southern Hemisphere were affected also, global disruption of the biosphere could ensue. In any event, there would be severe consequences, even in the areas not affected directly, because of the interdependence of the world economy. In either case the extinction of a large fraction of the Earth's animals, plants, and microorganisms seems possible. The population size of *Homo sapiens* conceivably could be reduced to prehistoric levels or below, and extinction of the human species itself cannot be excluded.

MT up to 10,000 MT, we now know that enough sunlight could be absorbed and scattered to cause widespread cold and darkness [(4, 5); these papers are also collectively referred to as TTAPS]. In each of these cases the computations indicate very serious biological consequences. This is so even though all the

scenarios are well within current capabilities and do not seem to be strategically implausible (1, 2, 4-6). Furthermore, the probability of nuclear wars of very high yield may have been generally underestimated (7). We also examine the consequences of the spread of atmospheric effects from the Northern to the Southern Hemisphere (4, 5).

As a reference case, we consider case 17 of the nuclear war scenarios discussed in TTAPS. This is a 10,000-MT exchange in which parameters describing the properties of dust and soot aerosols are assigned adverse but not implausible values and in which 30 percent of the soot is carried by fire storms to stratospheric altitudes. The resulting environmental perturbations, with their ranges of uncertainty, are listed for the Northern Hemisphere and the Southern Hemisphere in Table 1, A and B.

As an average over the Northern Hemisphere, independent of the season of the year, calculated fluxes of visible light would be reduced to approximately 1 percent of ambient, and surface temperatures in continental interiors could fall to approximately -40°C . At least a

year would be required for light and temperature values to recover to their normal conditions. In target zones, it might initially be too dark to see, even at midday. An estimated 30 percent of Northern Hemisphere mid-latitude land areas would receive a dose ≈ 500 R immediately after the explosions. This dose, from external gamma-emitters in radioactive fallout, would be comparable to or more than the acute mean lethal dose (LD_{50}) for healthy adults (8). Over the next few days and weeks, fallout would contribute an additional external dose of ≈ 100 R over 50 percent of northern mid-latitudes. Internal doses would contribute another ≈ 100 R concentrated in specific body systems, such as thyroid, bones, the gastrointestinal

This article was prepared following a meeting of biologists on the Long-Term Worldwide Biological Consequences of Nuclear War (Cambridge, Massachusetts, 25 and 26 April 1983). The consensus of the 40 scientists at the meeting is presented here, assembled by a committee consisting of: Paul R. Ehrlich, Stanford University; John Harte, University of California, Berkeley; Mark A. Harwell, Cornell University; Peter H. Raven, Missouri Botanical Garden; Carl Sagan, Cornell University; George M. Woodwell, Marine Biological Laboratory, Woods Hole; Joseph Berry, Carnegie Institute of Washington; Edward S. Ayensu, Smithsonian Institution; Anne H. Ehrlich, Stanford University; Thomas Eisner, Cornell University; Stephen J. Gould, Harvard University; Herbert D. Grover, University of New Mexico; Rafael Herrera, IVIC, Venezuela; Robert M. May, Princeton University; Ernst Mayr, Harvard University; Christopher P. McKay, National Research Council Associate; Harold A. Mooney, Stanford University; Norman Myers, Oxford, England; David Pimentel, Cornell University; and John M. Teal, Woods Hole Oceanographic Institution. The findings in this article were presented at the Conference on the World after Nuclear War, Washington, D.C., 31 October and 1 November 1983. Reprint requests should be sent to the Conference on the Long-Term Worldwide Biological Consequences of Nuclear War, 1735 New York Avenue, NW, Washington, D.C. 20006.

tract, and the milk of lactating mothers (9). After settling of the dust and smoke, the surface flux of near-ultraviolet solar radiation (UV-B, 320 to 290 nm) would be increased severalfold for some years, because of the depletion of the ozone-sphere by fireball-generated NO_x. Southern Hemisphere effects would involve minimum light levels < 10 percent of ambient, minimum land surface temperatures < -18°C, and UV-B increments of tens of percent for years. The potential impacts from the climatic changes that would be induced by nuclear war are outlined in Table 2.

Thermonuclear wars that would be less adverse to the environment are clearly possible, but climatic effects sim-

ilar to those just outlined could well result from much more limited exchanges, down to several hundred megatons, if cities were targeted (4, 5). Even if there were no global climatic effects, the regional consequences of nuclear war might be serious (Table 3). We believe, however, that decision-makers should be fully apprised of the potential consequences of the scenarios most likely to trigger long-term effects. For this reason we have concentrated in this article on the 10,000-MT severe case rather than the 5000-MT nominal baseline case of TTAPS. Because of synergisms, however, the consequences of any particular nuclear war scenario are likely to be still more severe than discussed below. We

still have too incomplete an understanding of the detailed workings of global ecosystems to evaluate all the interactions, and thus the cumulative effects, of the many stresses to which people and ecosystems would be subjected. Every unassessed synergism is likely to have an incremental negative effect.

Temperature

The impact of dramatically reduced temperatures on plants would depend on the time of year at which they occurred, their duration, and the tolerance limits of the plants. The abrupt onset of cold is of particular importance. Winter wheat, for

Table 1. Long-term stresses on the biosphere in (A) the Northern Hemisphere and (B) the Southern Hemisphere following a 10,000-MT severe Northern Hemisphere exchange (4, 5). Stresses occur simultaneously. Their geographic extent and severity would depend on many factors, including the number, distribution, and yield of the weapons detonated; height above the surface of the explosions and scale of the subsequent fires; degree of atmospheric transport of soot and dust (especially from the Northern to the Southern Hemisphere); and rate of washout of soot and dust, which determines their atmospheric residence times. Stresses in (B) are estimated effects which arise from 100-MT total detonations in the Southern Hemisphere plus particulates transported from the Northern Hemisphere primarily in the stratosphere. Data are from the "baseline 5000 MT" and "100-MT city attack" cases (4, 5). The Southern Hemisphere effects could be more severe if a heavy stratospheric soot burden resulted.

Physical parameter	Perturbed value*	Duration	Area affected†	Possible range
<i>A. Northern Hemisphere</i>				
Sunlight intensity	× 0.01	1.5 months	NML	× 0.003 to 0.03
	× 0.05	3 months	NML	× 0.01 to 0.15
	× 0.25	5 months	NH	× 0.1 to 0.7
	× 0.50	8 months	NH	× 0.3 to 1.0
Land surface temperature‡	-43°C	4 months	NML land	-53° to -23°C
	-23°C	9 months	NH land	-33° to -3°C
	-3°C	1 year	NH land	-13° to +7°C
UV-B radiation§	× 4	1 year	NH	× 2 to 8
	× 3	3 years	NH	× 1 to 5
Radioactive fallout exposure	≥ 500 R	1 hour to 1 day	30 percent NML land	Factor of 3
	≥ 100 R	1 day to 1 month	50 percent NML	
	≥ 10 R	≥ 1 month	50 percent NH	
Fallout burdens§,¶	¹³¹ I, 4 × 10 ⁵ MCi	8 days#	NML	
	¹⁰⁶ Ru, 1 × 10 ⁴ MCi	1 year	NH	
	⁹⁰ Sr, 400 MCi	30 years	NH	
	¹³⁷ Cs, 650 MCi	30 years	NH	
<i>B. Southern Hemisphere</i>				
Sunlight intensity	× 0.1	1 month	SH tropics	0.03 to 0.3
	× 0.5	2 months	SH tropics and SML	0.1 to 0.9
	× 0.8	4 months	SH	0.3 to 1.0
Land surface temperature‡	-18°C	1 month	SML land	-33° to -3°C
	-3°C	2 months	SML land	-23° to +7°C
	+7°C	10 months	SML land	-13° to +13°C
UV-B radiation§	× 1.5	1 year	SH	× 1.2 to 2.0
	× 1.2	3 years	SH	× 1.0 to 1.5
Radioactive fallout exposure	≥ 500 R	1 hour to 1 day	Near detonation sites	Factor of 3
	10 to 100 R	1 day to 1 month	SH land	
Fallout burdens§,¶	⁹⁰ Sr, 300 MCi	30 years	SH	
	¹³⁷ Cs, 330 MCi	30 years	SH	

*The following definitions apply: ×, multiplicative factor; R, rad = rem; MCi, megacurie. †Abbreviations: NH, Northern Hemisphere; NML, northern mid-latitudes; SH, Southern Hemisphere; SML, southern mid-latitudes. ‡Average surface temperatures should be compared to the normal ambient value of 13°C. §From (4, 5, 22). ¶These figures are rough estimates of whole-body gamma-ray doses and apply only to exposed organisms, particularly near or downwind of the 10⁴ explosion sites. Exposures are due to fallout on "prompt" and "intermediate" time scale; ingestion of biologically active radionuclides is not taken into account, but could double the dose in body organs (for instance, the thyroid for ¹³¹I), where these radionuclides tend to accumulate. Doses are larger than in some conventional models which scale from high-yield atmospheric tests; such models assume much more radioactivity carried into the stratosphere and decaying before falling out than is appropriate for a war with a wide mix of yields (4, 5, 40). #The principal modes of deposition are fallout and washout. In airbursts, the radionuclides settle out slowly over several years. In surface bursts, ~ 60 percent falls out promptly, ~ 40 percent over 1 to 2 years. In subsurface water bursts, ~ 100 percent is deposited in the water. During the atmospheric nuclear tests of the 1950's and 1960's, ~ 200 MT of fission yield produced an average ⁹⁰Sr deposition ~ 50 millicuries per square kilometer. #These are essentially the radionuclide lifetimes. Other radionuclides contribute mainly to the prompt fallout exposure.

tolerant plants could "harden" (develop freezing tolerance) before lethal temperatures were reached. Other stresses to plants from radiation, air pollutants, and low light levels immediately after the war would compound the damage caused by freezing. In addition, diseased or damaged plants have a reduced capacity to harden to freezing conditions (11).

Even temperatures considerably above freezing can be damaging to some plants. For example, exposure of rice or sorghum to a temperature of only 13°C at the critical time can inhibit grain formation because the pollen produced is sterile (11). Corn (*Zea mays*) and soybeans (*Glycine max*), two important crops in North America, are quite sensitive to temperatures below about 10°C.

While a nuclear war in the fall or winter would probably have a lesser effect on plants in temperate regions than one in the spring or summer, tropical vegetation is vulnerable to low temperatures throughout the year. The only areas in which terrestrial plants might not be devastated by severe cold would be immediately along the coasts and on islands, where the temperatures would be moderated by the thermal inertia of the oceans. These areas, however, would experience particularly violent weather because of the large lateral temperature gradient between oceans and continental interiors.

Visible Light

The disruption of photosynthesis by the attenuation of incident sunlight would have consequences that cascade through food chains, many of which include people as consumers. Primary productivity would be reduced roughly in proportion to the degree of light attenuation, even making the unrealistic assumption that the vegetation would remain otherwise undamaged.

Many studies have examined the effects of shading on the rate of photosynthesis, plant growth, and crop yield (12). Although individual leaves may be saturated by light levels below one-half of unattenuated sunlight, entire plants that have several layers of leaves oriented at different angles to the sun and partially shading each other are usually not light-saturated. Thus, while only a 10 percent reduction in light might not reduce photosynthesis in a fully exposed leaf, it might well reduce it in the entire plant because of the presence of unsaturated leaves within the canopy. Because plants also respire, most would, in fact, be

unlikely to maintain any net growth if the light level fell below about 5 percent of the normal ambient levels in their habitats (the compensation point) (12, 13). At the levels expected in the early months following a substantial nuclear exchange, plants would be severely affected and many would die because of the substantial reductions in their net productivity caused by reduced light alone.

Ionizing Radiation

Exposures to ionizing radiation in a nuclear exchange would result directly from the gamma and neutron flux of the fireball, from the radioactive debris deposited downwind of the burst, and from the component of the debris that becomes airborne and circulates globally.

The degree of injury to organisms would depend on the rate and magnitude of the exposure, with higher rates and larger total exposures producing more severe effects. The mean lethal exposure for human beings is commonly thought to be 350 to 500 R received in the whole body in less than 48 hours. Most other mammals and some plants have mean lethal exposures of less than 1000 R. If the rate of exposure is lower, the mean lethal dose rises.

The area subject to intense radiation from the fireball would also be affected directly by blast and heat (9, 14). The radius within which the pressure from the blast exceeds 5 pounds per square inch has been defined as the lethal zone (9) for blast, and the area within which the thermal flux exceeds 10 cal/cm² as the lethal zone for heat. The radius within which ionizing radiation from the fireball would be expected to be lethal for human beings is less than the radii for mortality defined by pressure or heat (1, 9). No special further consideration has been given here to the effects of ionizing radiation from the fireballs.

One estimate, based on the *Ambio* scenario (1) and similar to the TTAPS baseline case, involves an exchange of 5742 MT and about 11,600 detonations without overlapping fallout fields; it suggests that about 5×10^6 km² would be exposed to 1000 R or more in downwind areas. About 85 percent of this total exposure would be received within 48 hours. Such an exposure is lethal to all exposed people and cause the death of sensitive plant species such as most conifers—trees that form extensive forests over most of the cooler parts of the Northern Hemisphere. If nuclear reactors, radioactive waste storage facilities,

and fuel reprocessing plants are damaged during an exchange, the area affected and the levels of ionizing radiation could be even greater.

If we assume that approximately half of this area affected by fallout radiation in the range 1000 to 10,000 R is forested, there would be about 2.5×10^6 km² within which extensive mortality of trees and many other plants would occur (15). This would create the potential for extensive fires. Most conifers would die over an area amounting to about 2.5 percent of the entire land surface of the Northern Hemisphere.

The possibility that as much as 30 percent of the mid-latitude land area would be exposed to 500 R or more from gamma radiation emphasizes the scale and severity of the hazard (Table 1A). While 500 R of total exposure would have minor effects on most plant populations, it would cause widespread mortality among all mammals, including human beings. The unprotected survivors would be ill for weeks and more prone to cancer for the remainder of their lives. The total number of people afflicted would exceed 1 billion.

UV-B Radiation

In the weeks following the exchange, tropospheric and stratospheric dust and soot would absorb the UV-B flux that would otherwise be transmitted by the partially destroyed ozonosphere. But when the dust and soot cleared a few months later, the effects of O₃ depletion would be felt at the surface. In the Northern Hemisphere, the flux of UV-B would be enhanced for about a year by a factor of about 2 for the baseline TTAPS exchange and by a factor of 4 for the 10,000 MT war-treated in Table 1A. As is the case for an undepleted ozonosphere, the UV-B dose would be significantly greater at equatorial than at temperate latitudes.

Even much smaller O₃ depletions are considered dangerous to ecosystems and to people (16). If the entire UV-B band is enhanced by about 50 percent, the amount of UV-B at the higher energy end of the band, near 295 nm, would be increased by a factor of about 50. This region has particular biological significance because of the strong absorption of energy at these wavelengths by nucleic acids, aromatic amino acids, and the peptide bond. In large doses, UV-B is very destructive to plant leaves, weakening the plants and decreasing their productivity (17). Near-surface productivity

example, can tolerate temperatures as low as -15° to -20°C when preconditioned to cold temperatures (as occurs naturally in fall and winter months), but the same plants may be killed by -5°C if

exposed during active summer growth (10). Even plants from alpine regions, *Pinus cembra* for example, may tolerate temperatures as low as -50°C in midwinter but may be killed by temperatures of

-5° to -10°C occurring in summer (11). In the TTAPS calculations, temperatures are expected to fall rapidly to their lowest levels (Table 1); it is unlikely under these circumstances that normally cold-

Table 2. Potential impacts on humans and ecosystems from climatic changes induced by a major nuclear war at various time periods after the war.

First few months	End of first year	Next decade
Extreme cold, independent of season and widespread over the Earth, would severely damage plants, particularly in mid-latitudes in the Northern Hemisphere and in the tropics. Particulates obscuring sunlight would severely curtail photosynthesis, essentially eliminating plant productivity. Extreme cold, unavailability of fresh water, and near darkness would severely stress most animals, with widespread mortality. Storm events of unprecedented intensity would devastate ecosystems, especially at margins of continents. Temperature extremes would result in widespread ice formation on most freshwater bodies, particularly in the Northern Hemisphere and in mid-latitude continental areas. Marine ecosystems would be largely buffered from extreme temperatures, with effects limited to coastal and shallow tropical areas. Light reductions would essentially terminate phytoplankton productivity, eliminating the support base for many marine and freshwater animal species. Storms at continental margins would stress shallow-water ecosystems and add to sediment loadings. Potential food sources would not be accessible to humans or would be contaminated by radionuclides and toxic substances. Extreme temperatures and low light levels could preclude virtually any net productivity in crops anywhere on Earth. Supplies of food in targeted areas would be destroyed, contaminated, remote, or quickly depleted. Nontargeted importing countries would lose subsidies from North America and other food exporters. Survivors of immediate effects (from blast, fire, and initial ionizing radiation) would include perhaps 50 to 75 percent of the Earth's population. Extreme temperatures, near darkness, violent storms, and loss of shelter and fuel supplies would result in widespread fatalities from exposure, starvation, lack of drinking water, and synergisms with other impacts such as radiation exposure, malnutrition, lack of medical systems, and psychological stress. Societal support systems for food, energy, transportation, medical care, communications, and so on, would cease to function.	<i>Natural ecosystems: Terrestrial</i> Many hardy perennial plants and most seeds of temperate plants would survive, but plant productivity would continue to be depressed significantly. As the atmosphere clears, increased UV-B would damage plants and impair vision systems of many animal species. Limited primary productivity would cause intense competition for resources among animals. Many tropical species would continue to suffer fatalities or reduced productivity from temperature stress. Widespread extinction of vertebrates. <i>Natural ecosystems: Aquatic</i> Early loss of phytoplankton would continue to be felt in population collapses in many herbivore and carnivore species in marine ecosystems; benthic communities would not be as disrupted. Freshwater ecosystems would begin to thaw, but many species would have been lost. Organisms in temperate marine and freshwater systems adapted to seasonal temperature fluctuations would recover more quickly and extensively than in tropical regions. <i>Agroecosystems</i> Potential crop productivity would remain low because of continued, though much less extreme, temperature depressions. Sunlight would not be limiting but would be enriched with UV-B. Reduced precipitation and loss of soil from storm events would reduce potential productivity. Organized agriculture would be unlikely, and modern subsidies of energy, fertilizers, pesticides, and so on, would not be available. Stored food would be essentially depleted, and potential draught animals would have suffered extensive fatalities and consumption by humans. <i>Human-societal systems</i> Climatic impacts would be considerably reduced, but exposure would remain a stress on humans. Loss of agricultural support would dominate adverse human health impacts. Societal systems could not be expected to function and support humans. With the return of sunlight and UV-B, widespread eye damage could occur. Psychological stresses, radiation exposures, and many synergistic stresses would continue to affect humans adversely. Epidemics and pandemics would be likely.	Basic potential for primary and secondary productivity would gradually recover; however, extensive irreversible damage to ecosystems would have occurred. Ecosystem structure and processes would continue to respond unstably to perturbations and a long period of time might follow before functional redundancies would reestablish ecosystem homeostasis. Massive loss of species, especially in tropical areas, would lead to reduced genetic and species diversity. Recovery would proceed more rapidly than for terrestrial ecosystems. Species extinctions would be more likely in tropical areas. Coastal marine ecosystems would begin to contain harvestable food sources, although contamination could continue. Biotic potential for crop production would largely be restored. Limiting factors for reestablishment of agriculture would be related to human support for water, energy, fertilizers pest and disease protection, and so on. Climatic stresses would not be the primary limiting factors for human recovery. Rates of reestablishment of societal order and human support systems would limit rates of human population growth. Human carrying capacities could remain severely depressed from prewar conditions for a very long period of time, at best.

rectly; food resources would become scarce in a very short time. Further, nations that now require large imports of foods, including those untouched by nuclear detonations, would suffer an immediate interruption of the flow of food, forcing them to rely solely on their local agricultural and natural ecosystems. This would be very serious for many less-developed countries, especially those in the tropics.

Most major crops are annuals that are highly dependent on substantial energy and nutrient subsidies from human societies. Further, the fraction of their yields available for human consumption requires excess energy fixation beyond the respiratory needs of the plants, depending on full sunlight, on minimization of environmental stresses from pests, water insufficiency, particulates, and air pollution, and so on. Providing these conditions would be far more difficult, if not impossible, over much, if not all, of the Earth following a nuclear exchange. Agriculture as we know it would then, for all practical purposes, have come to an end.

Since the seeds for most North American, European, and Soviet crops are harvested and stored not on individual farms but predominantly in or near target areas, seed stocks for subsequent years would almost certainly be depleted severely, and the already limited genetic variability of those crops (24) would probably be reduced drastically. Furthermore, the potential crop-growing areas would experience local climatic changes, high levels of radioactive contamination, and impoverished or eroded soils. Recovery of agricultural production would have to occur in the absence of the massive energy subsidies (especially in the form of tractor fuel and fertilizers) to which agriculture in developed countries has become adapted (25).

Except along the coasts, continental precipitation would be reduced substantially for some time after a nuclear exchange (4, 5). Even now, rainfall is the major factor limiting crop growth in many areas, and irrigation, with requirements for energy and human support systems for pumping ground water, would not be available after a war. Moreover, in the months after the war, most of the available water would be frozen, and temperatures would recover slowly to normal values (26).

Temperate Terrestrial Ecosystems

The 2 billion to 3 billion survivors of the immediate effects of the war would

be forced to turn to natural ecosystems as organized agriculture failed. Just at the time when these natural ecosystems would be asked to support a human population well beyond their carrying capacities, the normal functioning of the ecosystems themselves would be severely curtailed by the effects of nuclear war.

Subjecting these ecosystems to low temperature, fire, radiation, storm, and other physical stresses (many occurring simultaneously) would result in their increased vulnerability to disease and pest outbreaks, which might be prolonged. Primary productivity would be dramatically reduced at the prevailing low light levels; and, because of UV-B, smog, insects, radiation, and other damage to plants, it is unlikely that it would recover quickly to normal levels, even after light and temperature values had recovered. At the same time that their plant foods were being limited severely, most, if not all, of the vertebrates not killed outright by blast and ionizing radiation would either freeze or face a dark world where they would starve or die of thirst because surface waters would be frozen and thus unavailable. Many of the survivors would be widely scattered and often sick, leading to the slightly delayed extinction of many additional species.

Natural ecosystems provide civilization with a variety of crucial services in addition to food and shelter. These include regulation of atmospheric composition, moderation of climate and weather, regulation of the hydrologic cycle, generation and preservation of soils, degradation of wastes, and recycling of nutrients. From the human perspective, among the most important roles of ecosystems are their direct role in providing food and their maintenance of a vast library of species from which *Homo sapiens* has already drawn the basis of civilization (27). Accelerated loss of these genetic resources through extinction would be one of the most serious potential consequences of nuclear war.

Wildfires would be an important effect in north temperate ecosystems, their scale and distribution depending on such factors as the nuclear war scenario and the season. Another major uncertainty is the extent of fire storms, which might heat the lower levels of the soil enough to damage or destroy seed banks, especially in vegetation types not adapted to periodic fires. Multiple airbursts over seasonally dry areas such as California in the late summer or early fall could burn off much of the state's forest and brush areas, leading to catastrophic flooding and erosion during the next rainy season. Silting, toxic runoff, and rainout of radio-

nuclides could kill much of the fauna of fresh and coastal waters, and concentrated radioactivity levels in surviving filter-feeding shellfish populations could make them dangerous to consume for long periods of time.

Other major consequences for terrestrial ecosystems resulting from nuclear war would include: (i) slower detoxification of air and water as a secondary result of damage to plants that now are important metabolic sinks for toxins; (ii) reduced evapotranspiration by plants contributing to a lower rate of entry of water into the atmosphere, especially over continental regions, and therefore a more sluggish hydrologic cycle; and (iii) great disturbance of the soil surface, leading to accelerated erosion and, probably, major dust storms (28).

Revegetation might superficially resemble that which follows local fires. Stresses from radiation, smog, erosion, fugitive dust, and toxic rains, however, would be superimposed on those of cold and darkness, thus delaying and modifying postwar succession in ways that would retard the restoration of ecosystem services (29). It is likely that most ecosystem changes would be short term. Some structural and functional changes, however, could be longer term, and perhaps irreversible, as ecosystems undergo qualitative changes to alternative stable states (30). Soil losses from erosion would be serious in areas experiencing widespread fires, plant death, and extremes of climate. Much would depend on the wind and precipitation patterns that would develop during the first postwar year (4, 5). The diversity of many natural communities would almost certainly be substantially reduced, and numerous species of plants, animals, and microorganisms would become extinct.

Tropical Terrestrial Ecosystems

The degree to which the tropics would be subjected to the sorts of conditions described above depends on factors such as the targeting pattern (1, 6), the prevalence of fire storms, the breakdown of the distinction between troposphere and stratosphere, and the rate of interhemispheric mixing as a function of altitude (4, 5). The spread of dense clouds of dust and soot and subfreezing temperatures to the northern tropics is highly likely, and to the Southern Hemisphere at least possible, so that it is appropriate to discuss the probable consequences of such a spread (4, 5) (Table 1B).

For example, the seeds of trees in tropical forests tend to be much more

of marine plankton is known to be depressed significantly by contemporary ambient UV-B levels; even small increases in UV-B could have "profound consequences" for the structure of marine food chains (16).

There are at least four additional ways in which increased levels of UV-B are known to be harmful to biological systems: (i) the immune systems of *Homo sapiens* and other mammals are known to be suppressed even by relatively low doses of UV-B (18). Especially under conditions of increased ionizing radiation and other physiological stress, such suppression of the immune systems leads to an increase in the incidence of disease. (ii) Plant leaves that reach maturity under low light intensities are two to three times more sensitive to UV-B than leaves that develop under high light intensities (19). (iii) Bacterial UV-B sensitivity is enhanced by low temperatures, which suppress the normal process of DNA repair, a process that is dependent on visible light (16). (iv) Protracted exposure to increased UV-B may induce corneal damage and cataracts, leading to blindness in human beings and terrestrial mammals (20). Thus the effects of increased UV-B may be among the most serious unanticipated consequences of nuclear war.

Atmospheric Effects

In a nuclear war, large quantities of air pollutants, including CO, O₃, NO_x, cyanides, vinyl chlorides, dioxins, and furans would be released near the surface (4, 5, 21). Smog and acid precipitation would be widespread in the aftermath of the nuclear exchange. These toxins might not have significant immediate effects on the vegetation that was already devastated, although, depending upon their persistence, they could certainly hinder its recovery. Their atmospheric transport by winds to more distant, initially unaffected ecosystems, on the other hand, might be an important additional effect. Large-scale fires coupled with an interruption of photosynthetic CO₂ uptake would produce a short-term increase in the atmospheric CO₂ concentration. The quantity of CO₂ now in the atmosphere is equivalent to that used by several years of photosynthesis and is further buffered by the inorganic carbon reserves of the ocean (22). Therefore, if the global climate and photosynthetic productivity of ecosystems recovered to near-normal levels within a few years, it is unlikely that any significant long-term change in the composition of the atmosphere would occur. It is not beyond the realm of possibility, however, that an

event encompassing both hemispheres, with the ensuing damage to photosynthetic organisms, could cause a sudden increase in CO₂ concentration and thus long-term climatic changes. For comparison, the time scale for recycling of O₂ through the biosphere is about 2000 years (23).

Agricultural Systems

There is little storage of staple foods in human population centers, and most meat and fresh produce are supplied directly from farms. Only cereal grains are stored in significant quantities, but the sites at which they are stored often are located in areas remote from population centers. Following a spring or early summer war, the current year's crops would almost certainly be lost. Cereal crops would be harvested before a fall or winter war, but since the climate would remain unusually cold for many months, the following growing season would also be unfavorable for crop growth.

After a nuclear war, in short, the available potential supplies of food in the Northern Hemisphere would be destroyed or contaminated, located in inaccessible areas, or rapidly depleted. For nations experiencing the nuclear war di-

Table 3. Potential ecological consequences of the reference nuclear war, other than those induced by temperature and light reductions.

Stress	Intensity or extent	Mechanisms of effects	Ecosystem consequences
Local, global radioactive fallout from nuclear detonation*	≥ 100 rem average background; ≥ 200 rem over large area in Northern Hemisphere*	Direct health effects; immune system depression; differential radiosensitivities of species; genetic effects	Alteration in trophic structures; pest outbreaks; replacement by opportunistic species; genetic and ontogenetic anomalies
Enhanced UV-B	Fourfold increase over Northern Hemisphere*	Suppression of photosynthesis; direct health effects; differential sensitivities of species; damage to vision systems; immune system depression	Reduction in primary productivity; alterations in marine trophic structures; blindness in terrestrial animals; behavioral effects in insects including essential pollinators
Fire	Secondary fires widespread over Northern Hemisphere; ≥ 5 percent of terrestrial ecosystems affected	Direct loss of plants; damage to seed stores; changes in albedo; habitat destruction	Deforestation and desertification, which continues through positive feedback (39); local climatic changes; large-scale erosion and siltation; nutrient dumping; species extinction
Chemical pollution of surface waters	Pyrotoxins; release from chemical storage areas	Direct health effects; differential sensitivities of species; bioconcentration	Loss of organisms; continued contamination of surface and ground water systems; loss of water for human consumption
Chemical pollution of atmospheres	Major releases of NO, O ₃ and pyrogenic pollutants from detonations; major releases of toxic organics from secondary fires in urban areas and chemical storage facilities	Direct health effects; differential sensitivities of species; acid precipitation	Widespread smog; freshwater acidification; nutrient dumping

*See Table 1A.

short-lived than those of temperate zones. If darkness or cold temperatures, or both, were to become widespread in the tropics, the tropical forests could largely disappear. This would lead to extinction of most of the species of plants, animals, and microorganisms on the Earth (31, 32), with long-term consequences of the greatest importance for the adaptability of human populations.

If darkness were widespread in the tropics, vast areas of tropical vegetation, which are considered very near the compensation point (33), would begin to respire away. In addition, many plants in tropical and subtropical regions do not have dormancy mechanisms that enable them to tolerate cold seasons, even at temperatures well above freezing. Even if the darkness and cold were confined mainly to temperate regions, pulses of cold air and soot could carry quick freezes well into the tropics. This would amount to an enhanced case of the phenomenon known as "friagem," which is used to describe the effects of cool temperatures spreading from temperate South America and entering the equatorial Amazon Basin, where they kill large numbers of birds and fish (34). One can predict from existing evidence on cooling effects during the Pleistocene and their consequences (35) that continental low-latitude areas would be severely affected by low air temperatures and decreased precipitation.

The dependence of tropical peoples on imported food and fertilizer would lead to severe effects, even if the tropics were not affected directly by the war. Large numbers of people would be forced to leave the cities and attempt to cultivate the remaining areas of forest, accelerating their destruction and the consequent rate of extinction. These activities would also greatly increase the amount of soot in the atmosphere, owing to improvised slash-and-burn agriculture on a vast scale. Regardless of the exact distribution of the immediate effects of the war, everyone on the Earth would ultimately be affected profoundly.

Aquatic Ecosystems

Aquatic organisms tend to be buffered against dramatic fluctuations in air temperature by the thermal inertia of water. Nevertheless, many freshwater systems would freeze to considerable depths or completely because of the climatic changes after a nuclear war. The effect of prolonged darkness on marine organisms has been estimated (36). Primary producers at the base of the marine food chain

are particularly sensitive to prolonged low light levels; higher trophic levels are subject to lesser, delayed propagated effects. Moreover, the near-surface productivity of marine plankton is depressed significantly by present UV-B levels; even small increases in UV-B could have profound consequences for the structure of marine food chains (16, 37). It is often thought that the ocean margins would be a major source of sustenance of survivors of a nuclear war; the combined effects of darkness, UV-B, coastal storms, destruction of ships in the war, and concentration of radionuclides in shallow marine systems, however, cast strong doubt on this.

Conclusions

The predictions of climatic changes are quite robust (4, 5), so that qualitatively the same types of stresses would ensue from a limited war of 500 MT or less in which cities were targeted (38) as from a larger scale nuclear war of 10,000 MT. Essentially, all ecosystem support services would be severely impaired (Tables 2 and 3). We emphasize that survivors, at least in the Northern Hemisphere, would face extreme cold, water shortages, lack of food and fuel, heavy burdens of radiation and pollutants, disease, and severe psychological stress—all in twilight or darkness.

The possibility exists that the darkened skies and low temperatures would spread over the entire planet (4, 5). Should this occur, a severe extinction event could ensue, leaving a highly modified and biologically depauperate Earth. Species extinction could be expected for most tropical plants and animals, and for most terrestrial vertebrates of north temperate regions, a large number of plants, and numerous freshwater and some marine organisms.

It seems unlikely, however, that even in these circumstances *Homo sapiens* would be forced to extinction immediately. Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects alone resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of over 1 billion people, the combined intermediate and long-term effects of nuclear

war suggest that eventually there might be no human survivors in the Northern Hemisphere. Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future (4, 5). In any large-scale nuclear exchange between the superpowers, global environmental changes sufficient to cause the extinction of a major fraction of the plant and animal species on the Earth are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

References and Notes

1. These analyses were reported in the series of articles published in *Ambio* 11, 76 (1982) and reprinted in J. Peterson, Ed., *The Aftermath: The Human and Ecological Consequences of Nuclear War* (Pantheon, New York, 1983).
2. S. Bergstrom *et al.*, "Effects of a nuclear war on health and health services," *WHO Publ. A36.12* (1983). These consequences follow from a presumed targeting strategy that includes most large cities in the Northern Hemisphere, to destroy adjacent military or industrial facilities and the leadership of various nations. Such widespread targeting derives in part from the large number of strategic warheads (almost 18,000) in the national arsenals and from the perceived unlikelihood of containment of a nuclear war once started; see also (5). Other previous studies of the consequences of nuclear war include: R. U. Ayres, *Environmental Effects of Nuclear Weapons* (H1-518-RR, Hudson Institute, New York, 1965); U.S. Arms Control and Disarmament Agency, *Effects of Nuclear War* (Washington, D.C., 1979); E. Ishikawa and D. L. Swain, Translators, *Hiroshima and Nagasaki, The Physical, Medical, and Social Effects of the Atomic Bombings* (Basic Books, New York, 1981); A. M. Katz, *Life after Nuclear War* (Ballinger, Cambridge, Mass., 1982); National Academy of Sciences, *Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonations* (Washington, D.C., 1975); Office of Technology Assessment, *The Effects of Nuclear War* (Washington, D.C., 1979); A. I. Thunberg, *Comprehensive Study on Nuclear Weapons* (United Nations, New York, 1981); A. H. Westing, *Warfare in a Fragile World* (Stockholm International Peace Research Institute, 1980); G. M. Woodwell, Ed., *Ecological Effects of Nuclear War* (Brookhaven National Laboratory, Upton, N.Y., 1963); B. Ramberg, *Destruction of Nuclear Energy Facilities in War* (Lexington Books, Lexington, Mass., 1980); K. N. Lewis, *Sci. Am.* 241, 35 (July 1979); J. C. Mark, *Annu. Rev. Nucl. Sci.* 26, 51 (1976); S. I. Auerbach and S. Warren, in *Survival and the Bomb: Methods of Civil Defense*, E. P. Wigner, Ed. (Indiana Univ. Press, Bloomington, 1969), p. 126; C. M. Haaland, C. V. Chester, E. P. Wigner, *Survival of the Relocated Population of the U.S. After a Nuclear Attack* (Oak Ridge National Laboratory, Oak Ridge, Tenn., 1979); *Nuclear Radiation in Warfare* (Stockholm International Peace Research Institute, Stockholm, 1981); J. P. Robinson, *The Effects of Weapons on Ecosystems* (United Nations Environment Program, United Nations, New York, 1979); P. R. Ehrlich, in *The Counterfeit Ark: Crisis Relocation for Nuclear War*, J. Leaning and L. Keyes, Eds. (Ballinger, Boston, 1983). Previous studies are reviewed in H. D. Grover, Ed., "The ecological consequences of nuclear war," report to the Ecological Society of America (in preparation).
3. P. R. Ehrlich, A. H. Ehrlich, J. P. Holdren, *Ecoscience: Population, Resources, Environment* (Freeman, San Francisco, 1977), p. 690.
4. R. P. Turco, O. B. Toon, T. Ackerman, J. B. Pollack, C. Sagan, *Science* 222, 1283 (1983).
5. —, in preparation.
6. National Academy of Sciences, *Long-Term Worldwide Effects of Multiple Nuclear Weapons Detonations* (Washington, D.C., 1975).
7. *Ambio* Advisors, *Ambio* 11, 94 (1982); D. Ball, *Adelphi Paper 169* (International Institute for Strategic Studies, London, 1981); P. Bracken and M. Shubik, *Technol. Soc.* 4, 155 (1981).
8. F. Barnaby and J. Rotblat, *Ambio* 11, 84 (1982).

9. S. Glasstone and P. J. Dolan, *Effects of Nuclear Weapons* (Department of Defense, Washington, D.C., 1977). The estimate for internal doses is crude. It is drawn from Glasstone and Dolan (pp. 597-609) and our experience. The thyroid exposure is commonly highest due to ^{131}I ; ^{90}Sr and ^{137}Cs also present significant internal hazards.
10. J. Levitt, *Responses of Plants to Environmental Stresses* (Academic Press, New York, 1980).
11. W. Larcher and H. Bauer, in: *Encyclopedia of Plant Physiology*, 12A, *Physiological Plant Ecology*, I, *Responses to the Physical Environment*, O. L. Lange, P. S. Nobel, C. B. Osmond, H. Ziegler, Eds. (Springer-Verlag, Berlin, 1981), p. 401.
12. O. Björkman, in *ibid.*, p. 57.
13. L. T. Evans, in *Plant Responses to Climatic Factors*, R. O. Slatyer, Ed. (Unesco, Paris, 1973), p. 22; A. L. Cristy and C. A. Porter, in *Photosynthesis*, vol. 2, *Development, Carbon Metabolism and Plant Productivity*, Govindjee, Ed. (Academic Press, New York, 1982), p. 499.
14. This is marginally less true for enhanced radiation weapons ("neutron bombs"). See, for example, S. T. Cohen, *The Neutron Bomb: Political, Technological and Military Issues* (Institute for Foreign Policy Analysis, Cambridge, Mass., 1978).
15. G. M. Woodwell and A. H. Sparrow, in *Ecological Effects of Nuclear War*, G. M. Woodwell, Ed. (Brookhaven National Laboratory, Upton, N.Y., 1963), p. 20.
16. C. H. Kruger et al. and R. B. Setlow et al., *Causes and Effects of Stratospheric Ozone Reduction: An Update* (National Academy of Sciences, Washington, D.C., 1982).
17. M. M. Caldwell, in *Encyclopedia of Plant Physiology*, 12A, *Physiological Plant Ecology*, I, *Responses to the Physical Environment*, O. L. Lange, P. S. Nobel, C. B. Osmond, H. Ziegler, Eds. (Springer-Verlag, Berlin, 1981), p. 169.
18. E. C. deFabo and M. L. Kripka, *Photochem. Photobiol.* 20, 385 (1979); W. L. Morison et al., *Br. J. Dermatol.* 101, 513 (1971); *J. Invest. Dermatol.* 75, 331 (1980); *ibid.* 76, 303 (1981); M. S. Fisher and M. L. Kripka, *Proc. Natl. Acad. Sci. U.S.A.* 74, 1688 (1977).
19. A. H. Teramura, R. H. Biggs, S. Kossuth, *Plant Physiol.* 65, 483 (1980); C. W. Warner and M. M. Caldwell, *Photochem. Photobiol.*, in press.
20. D. M. Pitts, in *Hearing on the Consequences of Nuclear War on the Global Environment* (97th Congress, 2nd Session, Serial No. 171, Government Printing Office, Washington, D.C., 1983), pp. 83-101.
21. P. J. Crutzen and J. W. Birks, *Ambio* 11, 114 (1982).
22. *The Global Carbon Cycle* (Scientific Committee on Problems of the Environment, Paris, 1979).
23. J. C. G. Walker, *The Evolution of the Atmosphere* (Macmillan, New York, 1978).
24. National Academy of Sciences, *Genetic Vulnerability of Major Crops* (Washington, D.C., 1972).
25. D. Pimentel et al., *Science* 182, 443 (1973).
26. Assuming the temperature of the ice-water interface is constant at 0°C , the thickness of the ice on a lake is given by $X = CT^{1/2}$, where T is the number of freeze days (essentially the area under the freezing point in a plot of temperature versus days) and $C = (2k/L)^{1/2}$, where k is the thermal conductivity of ice, s the specific density of ice, and L the heat of fusion of water [W. Furry, E. Purcell, J. Street, *Physics for Science and Engineering Students* (Blakiston, New York, 1952), p. 616]. If T is in thousands of days and X in meters, C is 0.026. The propagation depth of the impressed thermal wave for ice or for soils such as sandy clays is 1.5 m. Thus, not only will fresh water be unavailable on the continents but hundreds of millions of dead bodies thawing before the ground does would remain unburialable, at least until they were in advanced states of decay.
27. J. P. Holdren and P. R. Ehrlich, *Am. Sci.* 62, 282 (May-June 1974); F. H. Bormann, *BioScience* 26, 754 (1976); G. M. Woodwell, *ibid.* 24, 81 (1974); W. E. Westman, *Science* 197, 960 (1977).
28. This effect would be enhanced by nutrient dumping after major deforestation; see, for example, G. E. Likens et al., *Ecol. Monogr.* 40, 23 (1970).
29. G. M. Woodwell, *Science* 156, 461 (1967); *ibid.* 168, 429 (1970).
30. For example, R. M. May, *Nature (London)* 269, 471 (1977); C. S. Holling, *Annu. Rev. Ecol. Syst.* 4, 24 (1973); R. C. Lewontin, in "Diversity and stability in ecological systems," *USAEC Rep. BNL-501750* (1970).
31. A. Gómez-Pompa, C. Vázquez-Yanes, S. Guevara, *Science* 177, 762 (1972).
32. P. R. Ehrlich and A. H. Ehrlich, *Extinction: The Causes and Consequences of the Disappearance of Species* (Random House, New York, 1981); N. Myers, *A Wealth of Wild Species* (Westview, Boulder, Colo., 1983).
33. E. F. Brunig, *Forstarchiv* 42, 21 (1971).
34. A. Serrard and L. Rattisboma, *Bol. Geogr. Publ. Espec.* 3, 172 (1945).
35. J. P. Bradbury et al., *Science* 214, 1299 (1981); M. L. Salgado-Labouriau, *Rev. Palaeobot. Palynol.* 30, 297 (1980).
36. D. H. Milne and C. P. McKay, *Geol. Soc. Am. Spec. Pap.* 190 (1982). These modeling studies predicted that the reduction in sunlight corresponding to the scenario of Table 1 would at least devastate phytoplankton population levels. The biomass in the highest trophic level would be reduced by at least 20 percent for hundreds of days. This long period of stress could result in the extinction of many marine species, with effects being more severe for a spring or summer war.
37. J. Calkins, Ed., *The Role of Solar Ultraviolet Radiation in Marine Ecosystems* (Plenum, New York, 1982). For discussion of effects and concentration of radionuclides in the oceans, see National Academy of Sciences, *Radioactivity in the Marine Environment* (Washington, D.C., 1971).
38. The likelihood of a nuclear war remaining sufficiently limited so that major climatic and other effects would not ensue has been seriously questioned (7).
39. C. Sagan, O. B. Toon, J. B. Pollack, *Science* 206, 1363 (1979).
40. H. Lee and V. E. Strobe, *Stanford Res. Inst. Rep. EGU 2981* (1974).
41. We thank the other attendees at the biologists' meeting for their time and effort in discussing the issues dealt with here. The meeting was sponsored in part by the W. Alton Jones Foundation, whose support is gratefully acknowledged; S. J. Arden, J. A. Collins, M. Maki, and C. Fairchild provided invaluable organizational help. R. P. Turco and C. Sagan provided Table 1. R. L. Garwin, S. Gulmon, C. C. Harwell, R. W. Holm, S. A. Levin, M. M. Caldwell, O. B. Toon, and R. P. Turco kindly reviewed this article and made many helpful suggestions. D. Wheye and M. Maki provided substantial assistance in manuscript preparation.

RECEIVED
SEP 14 1980
AID : 50