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

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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

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 threshhold 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 (LLL) 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 10-15°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. 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

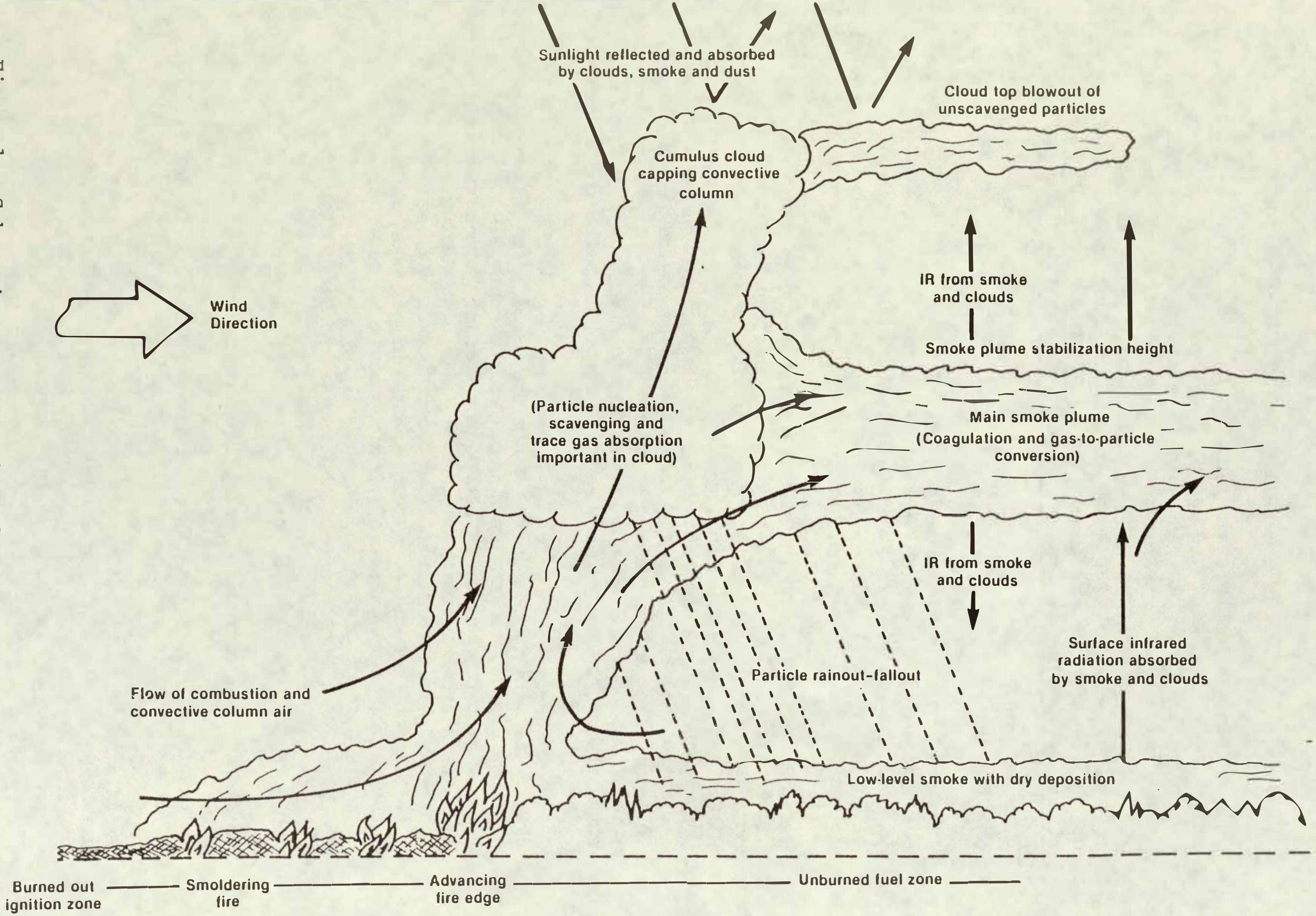

Figure 1: Schematic representation of major components of forest fires relevant to "nuclear winter" studies.

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

Component	Questions Addressed	Measurements
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

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 supermicrometer 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 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 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

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* 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.

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, C_2-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 NO_2), 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:

- 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
- Smoke Quantity and Character: Measured by specific gas detectors and a variety of passive and active particle sampling techniques
- Smoke Optical Properties: Determined from passive visible and infrared photometry, measurements of individual smoke particle scattering phase functions, and if possible, from transmissivity measurements of filter samples
- 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:

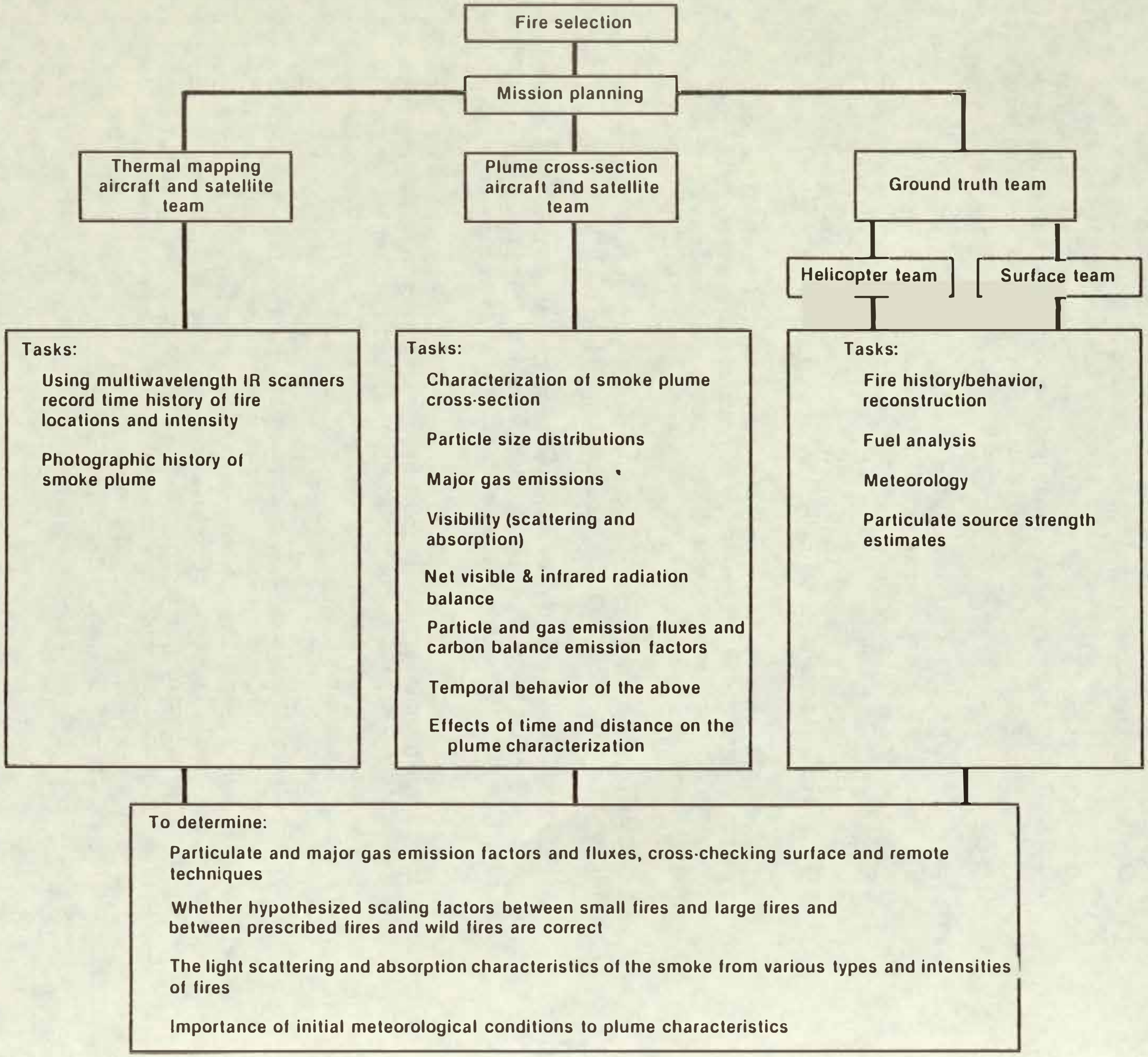

Figure 2: Initial concept for conducting fire experiment operations and measurements.

Table 3. Parameters to be Measured[*]

Parameter	Instrument
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 condensation 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 H_2O cloud and characteristics	Cloud particle size, spectrometers
Cloud removal efficiency for smoke	Particle size
Gaseous emissions special sensors	NDIR gas chromatographs,

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

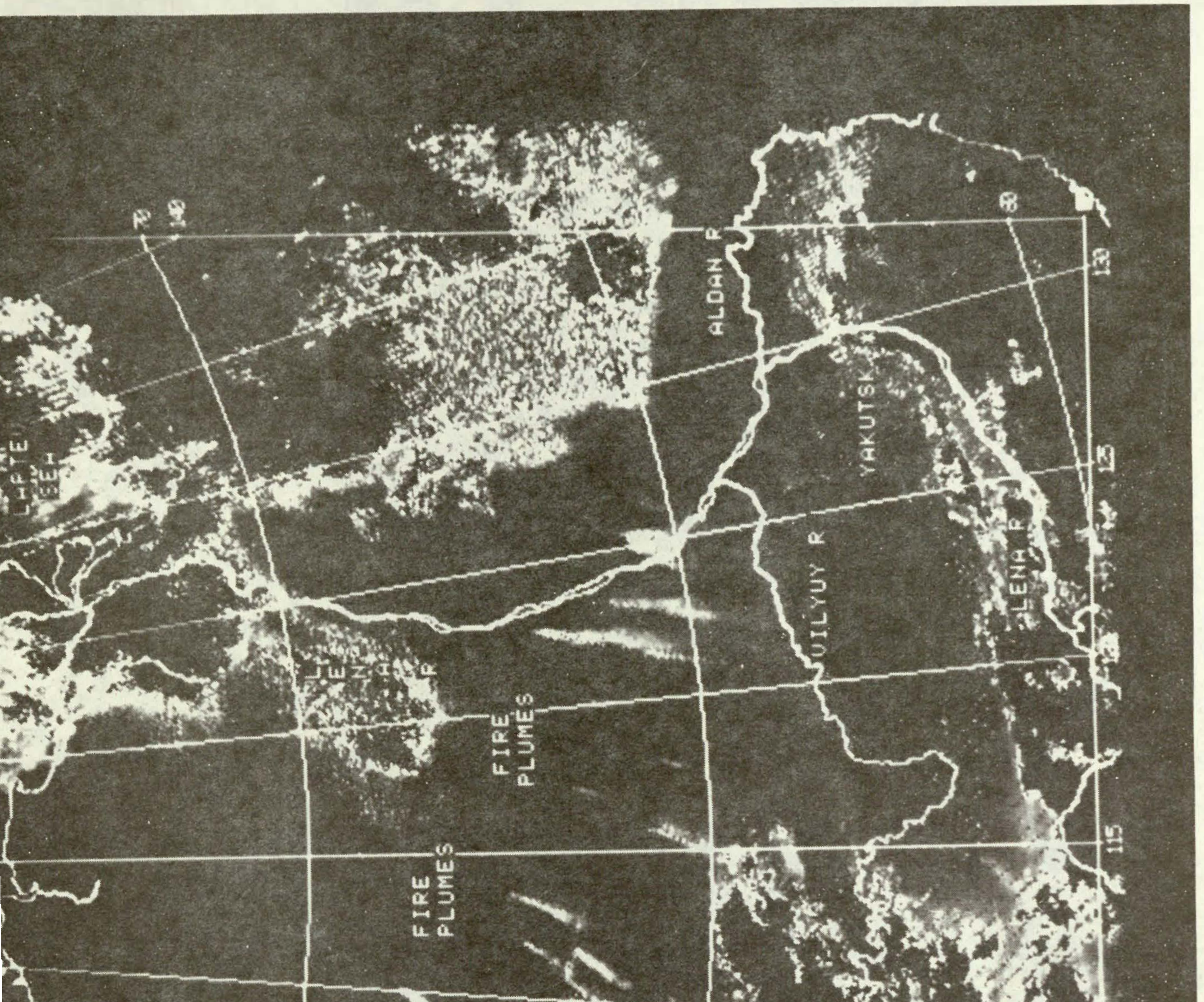

Figure 3: NOAA-7 imagery detected several large smoke plumes in Siberia from 10 to 25 July 1984.

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.

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*

Process	Analogues	Relevant observations
Soot particle source function	Urban fires (Moscow, 1812) San Francisco, 1906, etc.)	Total particle mass, Particle size distribution, Vertical distribution, Horizontal distribution, Optical properties of particles, if available
	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)	
Dust particle source function	Volcanic eruptions	(Same as soot particles)
	African dust storms	
	Arctic haze	
	Battlefield dust experiments	
	Road dust	
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

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* Compiled by Alan Robock, University of Maryland

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

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

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

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 mesocale 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 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

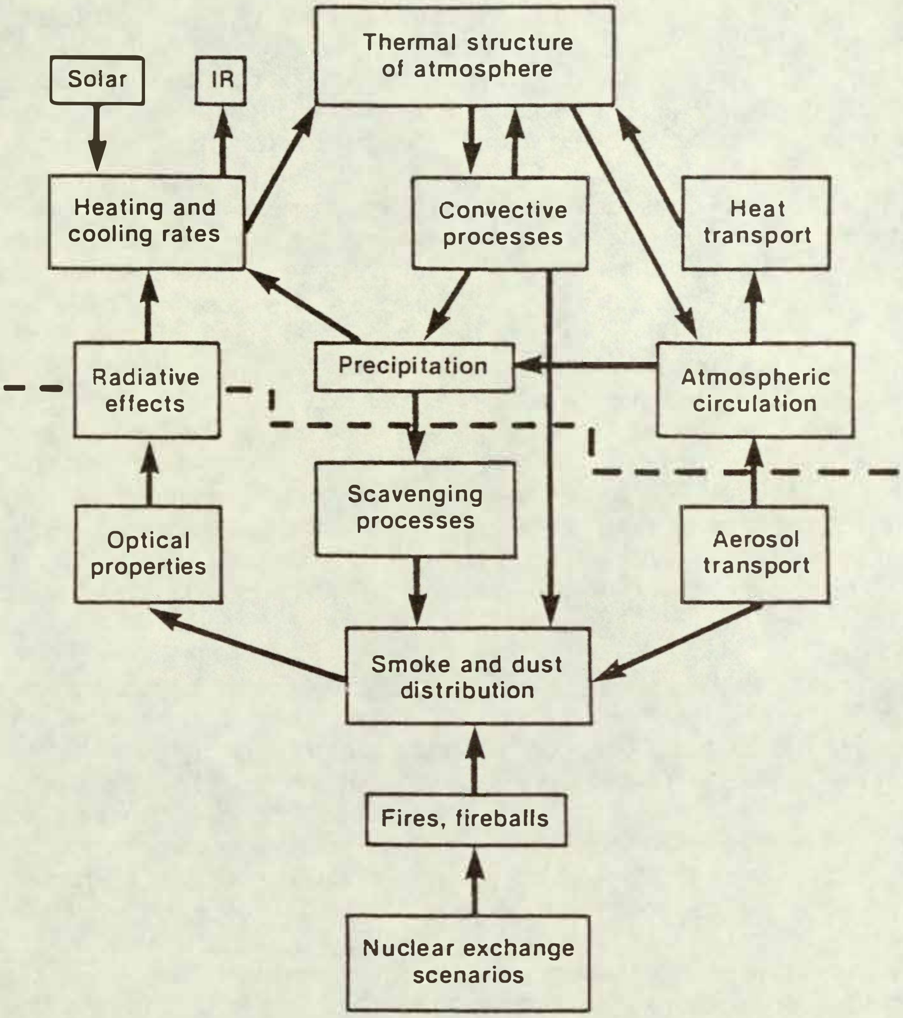

Figure 4: Principal physical processes required in global models to study the effects of nuclear explosions. Those processes above the dashed line are generally found in most global models; those below are not and require a concentrated effort.

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 relevent 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, "Extraterrestial 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

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APPENDIX A

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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 $<1.0\ \mu m$	$\sim 3 \times 10^{-2}$	10^{-3} - few 10^{-2}	Nature of fuel, nature of fire, fraction of fuel burned
Total aerosol mass (g)	$2 \times 10^{14} = 200$ Tg	10-1000 Tg	Present U.S. forest fire injection is about 10 Tg/yr, global atm soot loading <1 Tg

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 buffring 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