Fortieth session
Item 65 (h) of the provisional agenda

REVIEW OF THE IMPLEMENTATION OF THE RECOMMENDATIONS AND DECISIONS
ADOPTED BY THE GENERAL ASSEMBLY AT ITS TENTH SPECIAL SESSION:
PREVENTION OF NUCLEAR WAR

Climatic effects of nuclear war, including nuclear winter

Report of the Secretary-General

1. By its resolution 39/148 F of 17 December 1984, the General Assembly, inter alia, requested the Secretary-General to compile and distribute as a document of the United Nations appropriate excerpts of all national and international scientific studies on the climatic effects of nuclear war, including nuclear winter, published before 31 July 1985.

2. Pursuant to that request, the Secretary-General has the honour to transmit to the Assembly the compilation annexed hereto.

* A/40/150.

85-25291 1557-58n (E)
ANNEX

The climatic effects of nuclear war, including nuclear winter, a compilation of excerpts from national and international scientific studies

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

atm  atmosphere (measurement of air pressure)
C    Centigrade
C³   Command, control and communications
C³I  Command, control, communications and intelligence
Cal (cal) calorie
Ci   Curie
cm   centimetre
CO   carbon monoxide
CO₂  carbon dioxide
Cs   cesium
EPA  United States Environmental Protection Agency
g   gram
g/au² gram per square centimetre
h   hour
ICSU International Council of Scientific Unions
K    Kelvin
Kg   kilogram
Km   kilometre
Kt   kiloton
m   metre
mbar millibar
MT (mt) megaton
N    North
NCAR National Center for Atmospheric Research (United States)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>NH</td>
<td>Northern hemisphere (North hemisphere)</td>
</tr>
<tr>
<td>N</td>
<td>nitrogen</td>
</tr>
<tr>
<td>NO</td>
<td>nitric oxide</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>Odd nitrogen oxides - NO and NO(_2)</td>
</tr>
<tr>
<td>PAN</td>
<td>Peroxyacetyl nitrate</td>
</tr>
<tr>
<td>pH</td>
<td>potential of hydrogen</td>
</tr>
<tr>
<td>ppbv</td>
<td>parts per billion by volume</td>
</tr>
<tr>
<td>ppmv</td>
<td>parts per million by volume</td>
</tr>
<tr>
<td>psi</td>
<td>pounds per square inch</td>
</tr>
<tr>
<td>rads</td>
<td>The absorbed dose of any nuclear radiation which is accompanied by the liberation of 100 ergs of energy per gram of absorbing material</td>
</tr>
<tr>
<td>S</td>
<td>South</td>
</tr>
<tr>
<td>SCOPE</td>
<td>Scientific Committee on Problems of the Environment (ICSU)</td>
</tr>
<tr>
<td>SH</td>
<td>Southern hemisphere</td>
</tr>
<tr>
<td>Sr</td>
<td>strontium</td>
</tr>
<tr>
<td>Tg</td>
<td>teragram = 10(^{12}) grams</td>
</tr>
<tr>
<td>TTAPS</td>
<td>Turco, Toon, Ackerman, Pollack and Sagan</td>
</tr>
<tr>
<td>u (\text{\textmu}m)</td>
<td>micron</td>
</tr>
<tr>
<td>UV (uv)</td>
<td>ultra-violet</td>
</tr>
<tr>
<td>UV-B radiation</td>
<td>biologically damaging ultra-violet radiation</td>
</tr>
<tr>
<td>yr</td>
<td>year</td>
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I. INTRODUCTION

1. By resolution 39/148 F of 17 December 1984, the General Assembly requested the Secretary-General to compile and distribute as a document of the United Nations appropriate excerpts of all national and international scientific studies on the climatic effects of nuclear war, including nuclear winter. The resolution reads as follows:

"The General Assembly,

"Recalling that, in the Final Document of the Tenth Special Session of the General Assembly, 1/ after referring specifically to 'the threat to the very survival of mankind' posed by the existence of nuclear weapons, it declared, in paragraph 18, that removing the threat of a world war - a nuclear war - is the most acute and urgent task of the present day,

"Noting that, in spite of recent scientific endeavours, the environmental and other climatic consequences of a nuclear war still pose a major challenge to science,

"Noting that, as a result of recent atmospheric and biological studies, there have been new findings which indicate that in addition to blast, heat and radiation, nuclear war, even on a limited scale, would produce smoke, soot and dust of sufficient magnitude as to trigger an arctic nuclear winter which may transform the Earth into a darkened, frozen planet where conditions would be conducive to mass extinction,

"Recognizing that the prospect of nuclear winter poses an unprecedented peril to all nations, even those far removed from the nuclear explosions, which would add immeasurably to the previously known dangers of nuclear war,

"Conscious of the urgent need to continue and develop scientific studies to increase the knowledge and understanding of the various elements and consequences on climate, including nuclear winter,

"1. Requests the Secretary-General to compile and distribute as a document of the United Nations appropriate excerpts of all national and international scientific studies on the climatic effects of nuclear war, including nuclear winter, published so far or which may be published before 31 July 1985;

"2. Urges all States and intergovernmental organizations, as well as non-governmental organizations, through their intermediary, to transmit to the Secretary-General, prior to the above-mentioned date, the relevant material in their possession which may be useful for the above purpose;

1/ Resolution S-10/2.
3. Recommends that the above-mentioned document be examined at the fortieth session of the General Assembly in connection with the item dealing with the prevention of a nuclear war.

* * *

2. During the discussion in the General Assembly that led to the adoption of the resolution, it was made clear that the Secretariat should carry out the task within existing resources. In this context and in view of the very heavy workload of other documentation expected in 1985, the Secretariat indicated that for a document exceeding 100 final pages additional resources might have to be requested.

3. The present compilation of relevant extracts from scientific studies has been prepared with those constraints in mind. Efforts have been made to reflect the principal elements of major scientific studies that have contributed to the understanding of this complex subject, but in the circumstances it should be recognized that the compilation is selective. No judgement is intended or implied on the part of the United Nations concerning material included in or excluded from the compilation. Furthermore, in order to present information in its separate aspects, material is shown by subject-matter rather than study by study: for reasons of space, the reference notes of the excerpts quoted in the compilation have been excluded. For a fuller understanding of the arguments and evidence presented, the scientific studies themselves in their entirety should be consulted. Much other literature exists on the general subject and its specific aspects: for further reading a selective bibliography has been appended.

4. In connection with the preparation of the present document, material has been received from Australia, Canada, the German Democratic Republic, New Zealand, Sweden, the Union of Soviet Socialist Republics and the United Kingdom of Great Britain and Northern Ireland, and communications have been received from Cuba and India. Material has also been received from the United Nations Environment Programme, the World Meteorological Organization, the International Council of Scientific Unions (Scientific Committee on Problems of the Environment (SCOPE)) and the National Resources Defense Council, Inc.

II. BACKGROUND

5. The direct effects of nuclear weapons have been known for decades. It was recognized from the very beginning that nuclear weapons, in addition to being much more powerful, are qualitatively different from conventional explosive bombs that produce blast effects and heat. One such difference is the emission of radioactivity in the form of direct radiation that has its effect immediately in the vicinity of the explosion. In addition, the problem of "fallout" was discovered, radioactivity that is conveyed by the wind and can affect quite distant points sometime after the explosion. In the early 1970s, it was discovered that nuclear detonations could produce effects on the upper atmosphere and lead to the partial destruction of ozone in the stratosphere, with the implication that enhanced ultraviolet radiation, now shielded by the ozone layer, would be able to penetrate towards the surface of the earth and cause biological damage to people, animals and plants.
6. To this scenario has been added the idea of a nuclear winter. That concept is based on the proposition that large-scale fires and excavated debris produced by nuclear explosions in a major nuclear exchange would create a blanket of smoke and dust sufficient to reduce greatly the amount of sunlight reaching the Earth's surface. It has been predicted that in the ensuing darkness great cold would sweep across the continents with catastrophic consequences on crops, plants and animal life.

7. Interest in the subject was stimulated by a number of factors, among them the discovery during the Mariner 9 space probe in 1971 that dust storms on the planet Mars produced lower surface temperatures; the discovery that dust emitted by volcanoes into the stratosphere led to cooling at the Earth's surface, and the hypothesis that the impact of a meteorite hitting the earth some 65 million years ago put such quantities of dust into the atmosphere as to block out the sun and cause enough cooling to wipe out the basis for life support for the dinosaurs.

8. By 1975, when the United States National Academy of Sciences issued a report entitled *Long Term Worldwide Effects of Multiple Nuclear Weapons Detonations*, scientists had also identified the production of oxides of nitrogen in nuclear explosions as a major cause of concern. The report calculated that for the worst-case scenario of 10,000 mt yield, nitrogen oxides would lead to destruction of some 50 to 70 per cent of the ozone layer in the northern hemisphere; the intensity of damaging ultraviolet radiation reaching the ground would increase in consequence by a factor of 4 to 10. Ozone reduction in the southern hemisphere was estimated to reach a maximum of about 20 per cent one or two years after a nuclear war.

9. In 1982 a special issue of the journal *Ambio*, published by the Royal Swedish Academy of Sciences, was devoted entirely to articles on the effects of a major nuclear war. It included an article entitled "The Atmosphere after a Nuclear War: Twilight at Noon" in which Paul J. Crutzen and John W. Birks concluded that smoke from extensive forest, oil and gas fires following a nuclear war would drastically reduce the amount of sunlight reaching the Earth's surface. As a consequence, it was estimated that agricultural production in the northern hemisphere would be almost totally eliminated. Furthermore, as the smoke finally dispersed after a few months, world-wide photo-chemical smog would develop which, in turn, would interfere with agricultural production. Prior to Crutzen and Birks' work it had not been quantitatively demonstrated that the smoke from such fires could have a major hemispheric-scale impact on the atmosphere.

10. The *Ambio* article prompted a number of other groups to take up the issue. One such study of the effects of smoke generated by nuclear war was presented at the Conference on the World After Nuclear War, held at Washington, D.C., on 31 October and 1 November 1983, by a group (often referred to as TTAES, an acronym derived from the investigators' names: Richard Turco, Brian Toon, Thomas Ackerman, James Pollack and Carl Sagan) whose interest came in part from earlier studies of Martian dust storms. ("Nuclear Winter: Global Consequences of Multiple Nuclear Explosions" in *Science*, vol. 222 (23 December 1983), pp. 1283-1292.) It went another step beyond the Crutzen and Birks study by accounting for the smoke from burning cities.

/...
11. Scientists of the Union of Soviet Socialist Republics have also carried out studies on meteorological, climatological and ecological effects of nuclear explosions. (See "Global consequences of nuclear war: a review of recent Soviet studies" in World Armaments and Disarmament, SIPRI Yearbook 1983, pp. 107-129.) Several monographs published in the Soviet Union in the 1970s concentrated on the problems of the spread and fall-out of radioactive products, the impact upon the stratosphere ozone layer and the ecological consequences of a nuclear exchange. A new impetus to such studies was given by the All-Union Conference of Scientists for the Elimination of a Threat of Nuclear War that took place in Moscow in May 1983. In 1984 a report entitled Global Consequences of Nuclear War and the Developing Countries was prepared by the Committee of Soviet Scientists for Peace, against the Nuclear Threat, which, inter alia, dealt with the climatic consequences of nuclear war. The Soviet studies were in basic agreement with other findings that a nuclear conflict would have catastrophic effects on the Earth's climatic system.

12. Another contribution was made by Soviet and United States studies that used different three-dimensional climate models to stimulate the effects of a large-scale nuclear war on global climate. (See "Global Climatic Consequences of Nuclear War: Simulations with Three Dimensional Models" by S. L. Thompson, V. V. Aleksandrov, G. L. Stenchikov, S. H. Schneider, C. Covey and R. M. Chervin, in Ambio, vol. 13, No. 4, 1984, pp. 236-243.) The authors concluded that given a large amount of nuclear-war-generated smoke and dust above the first few kilometres in the atmosphere, one could expect strong land surface cooling in some regions, mid-atmospheric warming and profound changes in atmospheric circulation.

13. In December 1984, the United States National Academy of Sciences issued a report entitled The Effects on the Atmosphere of a Major Nuclear Exchange. Its general conclusion was that a major nuclear exchange would insert significant amounts of smoke, dust and chemicals into the atmosphere, which could result in dramatic perturbations of the atmosphere lasting over a period of at least a few weeks. Estimation of the amounts, the vertical distributions and the subsequent fates of these materials involves large uncertainties.

14. Also in 1984, the Minister of the Environment of Canada invited the Royal Society of Canada to prepare a report on the environmental and ecological consequences of major nuclear warfare, to include but not necessarily to be restricted to nuclear winter scenarios. The report, Nuclear Winter and Associated Effects, A Canadian Appraisal of the Environmental Impact of Nuclear War, which the Minister of the Environment received in February 1985, also tended to confirm that a drastic cooling would occur in the wake of a major nuclear war, owing chiefly to the vast amounts of carbon-rich smoke that would be carried round the world by the winds.

15. In March 1985, the United States Secretary of Defense submitted a report to the United States Congress entitled The Potential Effects of Nuclear War on the Climate, which, inter alia, stated that even with widely ranging and unpredictable weather, the destructiveness for human survival of the less severe climatic effects might be of a scale similar to the other horrors associated with nuclear war. The report recognized the importance of additional research to understand better the effects of nuclear war on the atmosphere but did not expect that reliable results would be rapidly forthcoming; as a consequence, there was a high degree of uncertainty, which would persist for some time.
16. On 12 September 1985, at the United States Academy of Sciences, Washington, D.C., on the occasion of the General Assembly of the Scientific Committee on Problems of the Environment (SCOPE), a report was made public on the project Environmental Consequences of Nuclear War (ENUWAR). The report is the result of a major co-operative effort among approximately 300 scientists from more than 30 countries stemming from resolutions adopted in 1982 by the General Assemblies of the International Council of Scientific Unions (ICSU) and SCOPE, one of the 10 Scientific Committees of ICSU. The first volume of the report deals with the climatic and atmospheric effects of a large-scale nuclear war and the second addresses the ecological, agricultural and human effects. Copies of the Foreword prepared by the Steering Committee and summaries of the two volumes were provided to the United Nations Secretariat by the Chairman of the Steering Committee in response to the request in General Assembly resolution 39/148 F.

III. METHODOLOGY, BASELINE CASES AND MODELS, AND THEIR CRITIQUE

17. Methodology for studying the nuclear phenomenon and its various aspects has evolved over the years from what seemed at the beginning unrelated calculations of the amount of smoke produced by forest and city fires to rather complex computer models of their climatic consequences according to a variety of baseline nuclear war scenarios. Following are some representative descriptions of that evolution and basic types of scenarios and models used as they appear in available sources.


"To study the optical and climatic effects of dust and smoke clouds generated in a nuclear war, the physicists ran computer models of dozens of different nuclear war scenarios. They adopted as a baseline case a 5,000 MT exchange with 20% of the explosive power (yield) expended on urban or industrial targets in the Northern Hemisphere. Given current arsenals, this is a realistic possibility for a full-scale war. Other cases studied ranged in total yield from 100 to over 10,000 MT.

In each case, the scientists calculated:

1. How much dust and smoke was generated;
2. How much sunlight was absorbed by the dust and smoke;
3. How much the temperature changed;
4. How the dust and smoke spread, and how long before it all fell back to the surface;
5. The extent of the radioactive fallout over time;
6. How much ultraviolet light reached the surface after the soot and dust fell out.

..."
From: Nuclear Winter and Associated Effects, A Canadian Appraisal of the
Environmental Impact of Nuclear War, report of the Committee on the
Environmental Consequences of Nuclear War, The Royal Society of Canada,

"... Three kinds of model have been used in nuclear winter studies:

(i) those in which variation of perturbation with height alone is assumed.
These one-dimensional (1-D) models may incorporate quite elaborate
details of the absorption, scattering and transmission of solar and
terrestrial radiation, but give no spatial details. They yield answers
for the entire planet, or for typical ocean and continental conditions
separately;

(ii) two-dimensional models (2-D), allowing variation of dust and smoke with
height and in the north-south (meridional) direction. Such models show
an average vertical cross-section from equator to pole, or from pole to
pole. They include simple representations of the way the atmosphere
redistributes materials injected in a specific latitude belt; and

(iii) three-dimensional (3-D) models that attempt a full spatial analysis, in
effect mapping the distribution of dust and smoke throughout the
atmosphere over a large area of the globe, show which regions are likely
to be most affected, and by how much. The most elaborate models
represent the whole earth, but are unable to account for local conditions
or variations which might prove critical to changes over much larger
areas.

The results obtained from modelling nuclear winter scenarios depend on the
adequacy of the estimated inputs of dust and smoke, and on the suitability of the
model used.

..."

* * *

From: "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions",
by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and
Copyright 1983 by the American Association for the Advancement of
Science.

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

Although the models we used can provide rough estimates of the average effects of widespread dust and smoke clouds, they cannot accurately forecast short-term or local effects. The applicability of our results depends on the rate and extent of dispersion of the explosion clouds and fire plumes. Soon after a large nuclear exchange, thousands of individual dust and smoke clouds would be distributed throughout the northern midlatitudes and at altitudes up to 30 km. Horizontal turbulent diffusion, vertical wind shear, and continuing smoke emission could spread the clouds of nuclear debris over the entire zone, and tend to fill in any holes in the clouds, within 1 to 2 weeks. Spatially averaged simulations of this initial period of cloud spreading must be viewed with caution; effects would be smaller at some locations and larger at others, and would be highly variable with time at any given location.

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

Scenarios

A review of the world's nuclear arsenals shows that the primary strategic and theater weapons amount to approximately 12,000 megatons (MT) of yield carried by approximately 17,000 warheads. These arsenals are roughly equivalent in explosive power to 1 million Hiroshima bombs. Although the total number of high-yield warheads is declining with time, about 7,000 MT is still accounted for by warheads of more than 1 MT. There are also approximately 30,000 lower-yield tactical warheads and munitions which are ignored in this analysis. Scenarios for the possible use of nuclear weapons are complex and controversial. Historically, studies of the long-term effects of nuclear war have focused on a full-scale exchange in the range of 5,000 to 10,000 MT. Such exchanges are possible, given the current arsenals and the unpredictable nature of warfare, particularly nuclear warfare, in which escalating massive exchanges could occur.

Our baseline scenario assumes an exchange of 5,000 MT. Other cases span a range of total yield from 100 to 25,000 MT. Many high-priority military and industrial assets are located near or within urban zones. Accordingly, a modest fraction (15 to 30 percent) of the total yield is assigned to urban or industrial targets. Because of the large yields of strategic warheads [generally greater than or approximately 100 kilotons (KT)] "surgical" strikes against individual targets /...
are difficult; for instance, a 100-KT airburst can level and burn an area of approximately 50 Km\(^2\), and a 1-MT airburst, approximately 5 times that area implying widespread collateral damage in any "countervalue", and many "counterforce", detonations.

The properties of nuclear dust and smoke are critical to the present analysis. ... For each explosion scenario, the fundamental quantities that must be known to make optical and climate predictions are the total atmospheric injections of fine dust (greater than or approximately 10 \(\mu\)m in radius) and soot.

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

...

* * *


"The intermediate and long-term effects of nuclear war have been considered in a number of past studies. Most of these have concentrated on radioactive fallout because of its potentially severe consequences. However, during the last decade it became apparent that the nitrogen oxides produced and injected into the stratosphere by large nuclear fireballs could significantly damage the ozone layer, and the consequent increase in ultraviolet B radiation reaching the earth's surface would have negative effects on the health of humans, animals and plants. Similarly, the potential of nuclear explosions to touch off widespread fires and to inject chemical pollutants or dust into the atmosphere has been known for years. However, the grave potential for adverse weather and climatic effects from massive amounts of smoke and dust has only recently been realized.

Crutzen and Birks concluded, via a simple order-of-magnitude estimate, that the forest fires ignited by a full-scale nuclear war could produce enough smoke to block sunlight over much of the Northern Hemisphere (NH) for a period of weeks or longer. They also suggested that the smoke produced by other sources such as gas, oil and urban fires could be "of enormous importance". Prior to Crutzen and Birks' work it had not been quantitatively demonstrated that the smoke from such fires could have a major hemispheric-scale impact on the atmosphere.

/...
The potential for a hemispheric-scale smoke cloud to create major alterations in atmospheric and surface temperatures was investigated in a subsequent study by Turco et al. The assessment of Turco et al., which confirmed Crutzen and Birks' basic point about the climatic importance of the aerosols, employed a one-dimensional radiative-convective global climate model, or RCM. In addition, Turco et al. used an aerosol model to predict the evolution and eventual removal of aerosols generated by a variety of nuclear war scenarios.

RCMs have routinely been used to study climatic changes, though they represent an extreme simplification of the behavior of the actual atmosphere. Basically, RCMs average all horizontal variations and consider quantities such as temperature and aerosol concentration to be functions only of altitude. Such models give only a globally averaged picture of the climate without regard for regional or seasonal variations. Nor can an RCM address the issue of how a perturbation originating in one region can affect other regions through atmospheric interactions -- e.g., by winds which transport heat. However, RCMs are economical with respect to computer usage and can excel at performing detailed radiative transfer calculations, important considerations for initial studies of the nuclear war-climate problem.

Recognizing the horizontally averaged nature of RCMs, Turco et al. performed two types of calculations. In the first type, the heat capacity of the surface was set low, in order to mimic the thermal inertia of a land surface. In this "all-land" case the aerosol injection scenarios resulted in a substantial decline in surface temperature. Within 30 days of the initial smoke injection the surface temperature dropped from a NH mean annual average of about 15°C to values well below the freezing point. Then, as the aerosols were removed from the atmosphere over the next few months the surface temperature gradually recovered to its initial value. During the time that the surface cooled, the atmospheric layer containing the smoke warmed. Both effects were caused by the absorption of sunlight by the smoke aerosol. As a result, a massive temperature inversion formed so that warmer air overlay cold air near the surface.

The results were very different when Turco et al. used a surface heat capacity characteristic of an all-ocean planet. The much greater thermal inertia in this case resulted in only a small drop in surface temperature (less than 3°C after six months). In the real atmosphere, of course, both cases could occur at once; land areas under the smoke would be expected to cool much more than the oceans. Furthermore, areas of the globe not initially covered by smoke -- e.g., the tropics and the Southern Hemisphere (SH) -- would be expected to suffer a much smaller temperature perturbation.

Since atmospheric motions tend on average to transport heat from warmer to cooler areas, the cooling of land surfaces envisioned by Turco et al. would be ameliorated to some degree by the transport of heat from the high heat capacity oceans and from other areas which suffered much less cooling. Turco et al. extrapolated the results of other simple climate models to estimate that the magnitude of the land temperature drop could be reduced by about 20% in the middle of continents and 40% near the coasts. However, they also speculated that a disruption of normal atmospheric circulation created by aerosol-induced heating contrasts might spread the aerosols well beyond their original latitudes of injection, perhaps into the SH.
The results of the RCM by Turco et al. has been largely duplicated by calculations with other one dimensional models. MacCraken reported results from both a one-dimensional RCM and a two-dimensional model using the same nuclear aerosol scenarios. The one-dimensional model gave a maximum land surface cooling of about 30°C, in rough agreement with Turco et al. Although only latitude and height were resolved in the two-dimensional model, the moderating effect of the oceans was allowed for by approximating the thermal mixing between land and sea. In this case the average cooling of land areas underlying the smoke was about 15°C after two weeks. The limitations of spatially averaged models, in terms of both estimating average land surface cooling and determining regional effects has prompted two groups working independently to use three-dimensional atmospheric models to examine this important problem in more detail.

The General Circulation Models

The atmosphere in a general circulation model (GCM) is described by mathematical representations of basic physical laws -- e.g., conservation of mass and energy, and Newton's second law of motion. However, whereas the atmosphere is a continuous fluid, computational constraints force us to discretize our model atmospheres. That is, we must approximate the continuous equations by solving only for a finite number of variables (e.g., temperature, pressure) on a discrete grid mesh covering the earth horizontally and vertically. The process of "discretization" implies that the models cannot resolve certain small-scale features and processes that we know to be important in determining the large-scale atmospheric circulation and temperatures. These "sub-grid scale" processes must be represented in terms of the large-scale fields, a process called parameterization. Cloud formation, precipitation, and turbulent/radiative heat transfer at the Earth's surface are examples of parameterized processes in GCMs.

A GCM recently developed at the National Center for Atmospheric Research in the U.S. [referred to here as the NCAR model] represents the atmosphere and surface by approximately 4.5° latitude and 7.5° longitude resolution with 9 layers from the surface through the troposphere and stratosphere to an altitude of about 30 km. The version reported on here uses prescribed solar insolation, ocean surface temperatures, sea ice, ozone and snowcover for the particular time of year being simulated. The massive heat capacity of the upper mixed layer of the ocean assures that the relatively short (less than a few months) simulations described here will not be noticeably compromised by assuming non-interacting oceans. On the other hand, land surface temperatures are computed assuming a zero heat capacity surface, an approximation which is reasonable for time scales longer than a few days. Simulations were performed with this model starting at several different points on the annual cycle.

The model employed at the Computing Centre of the U.S.S.R. Academy of Sciences [referred to here as the CCAS model] has a horizontal resolution of 12° latitude by 15° longitude with two vertical layers representing the troposphere from the surface to an altitude of about 12 km (20 kPa). Unlike the NCAR model, the CCAS model computes the change in ocean surface temperatures through the use of a coupled thermodynamic model of the upper ocean. CCAS model simulations use annually averaged solar energy and thus are intended to be representative of annual mean conditions rather than individual seasons.

/...
Both the NCAR and CCAS models specify actual continental locations and topographic heights consistent with their resolution. Large scale atmospheric motions and temperatures are generated, as in reality, by the non-uniform absorption of solar energy and its subsequent transformation to sensible heat, potential and kinetic energies through radiative, condensational and turbulent processes. Both models include parameterizations for precipitation and for clouds that form and dissipate as determined by relative humidity and convective activity. The basic atmospheric simulations of both models are in reasonable agreement with most important observational variables.

..."  

* * *


"The Baseline Nuclear Exchange

The conclusions of any study of the consequences of nuclear war depend on the level and nature of the weapons exchange. The baseline case for this study, consistent with the mission statement, depicts a major nuclear war between the United States and the Soviet Union. The committee has not chosen the baseline assumptions to depict either the "most likely" general war scenario or the "worst-case" general war scenario. In defining the baseline case, the committee has sought to establish a credible, generalized account of the extent of a possible general nuclear war in the mid-1980s; hence it is not necessary to specify the manner in which this general war might begin or might escalate from the initial use of nuclear weapons or to designate specific weapons for specific targets.

United States and Soviet nuclear forces reportedly now include about 50,000 nuclear weapons, with a total yield of some 13,000 Mt. About 25,000 of these nuclear weapons, with a yield of about 12,000 Mt, are on systems with strategic or major theater missions. The other 25,000 weapons, mostly of much smaller yield, are designed for tactical battlefield, air defense, antisubmarine, naval, and other special missions. In this analysis the committee has assumed that approximately one-half of these weapons, or 25,000, would actually be detonated, with a total yield of about 6,500 Mt. This would include 12,500 strategic and major theater weapons with a yield of 500 Mt. The fraction of one-half has been applied to take into account the following factors that would reduce the number of weapons actually delivered on target: weapons destroyed by counterforce attacks, weapons systems unreliable under combat conditions, and weapons held in reserve. This assumption should be within a factor of 2 of the exchange in a general nuclear war.

The weapons in this exchange are all assumed to be 1.5 Mt or less, with a major fraction less than 1.0 Mt. This represents a shift from many earlier analyses, which included significant numbers of 10- and 20-Mt bombs and missile warheads. The elimination of very high yield weapons reflects the fact that both nations have, in recent years, been increasing to obtain larger numbers of lower yield warheads. Similarly, multimegaton bombs have been replaced by more and
smaller bombs and by large numbers of stand-off cruise missiles with smaller yields. By 1985, there will probably be few, if any, multimegaton weapons deployed by either the United States or the Soviet Union, unless present trends are reversed.

In a general nuclear war between the United States and the Soviet Union, the Committee has assumed that all member nations of NATO and the Warsaw Pact would be involved and targeted for strategic weapons. The significance of this assumption to the study is that a number of targets located in urban areas, which are the major source of smoke, are found outside the United States and Soviet Union. It is further assumed that tactical nuclear war would for the most part be confined to the NATO/WARSAW Pact area (European Front) and the oceans. While other key allies and countries could well become involved in such a conflict, the committee did not have a specific military rationale for including targets in these nations. Moreover, modest numbers of military targets in such countries would not significantly alter the study results.

The description of specific targets in all of these countries for 12,500 strategic and major theater weapons would be a difficult undertaking with no enduring validity. Even if the specific targeting plans of the nuclear powers were adopted, such detail could be misleading in suggesting that there would be a unique predictable pattern to a general nuclear exchange. Moreover, such detail is not relevant to this study, which relies on models that do not have as inputs the actual locations of targets. Factors such as proximity to oceans might be important to more sophisticated future models.

The committee has assumed that each side would give highest priority to "counterforce" attacks against the vulnerable components of the other side's threatening strategic forces and against the command, control, communications, and intelligence (C3I) facilities necessary to operate those forces effectively. It is also assumed that high priority would be given to destroying key military bases and transportation and communications nodes necessary for theater operations, particularly in Europe. The committee has assigned approximately 9,000 effective warheads with a yield of some 5,000 Mt to these missions. This would be consistent with each side's attacking each of the other side's strategic missile silos with two weapons in order to improve the kill probability; multiple attacks on several hundred military and civilian airfields capable of sustaining redeployed strategic aircraft; multiple attacks on submarine and naval bases; extensive attacks against the central civilian and military command and control systems, the critical nodes in the military communications systems and facilities necessary to exploit intelligence assets for real-time targeting and damage assessment; and multiple attacks on several hundred major theater military targets.

The committee assumed that each side would, as a second priority, attack the other's economic base necessary to sustain its military efforts. These "countervalue" targets would include plants producing military equipment, important components, and materials, petroleum refineries and storage, and electric power plants, as well as key transportation and communication nodes. In this scenario, some 3,500 effective warheads with a yield of 1,500 Mt would be used against such targets.
While neither side would target population per se, the committee has assumed that neither would refrain from attacking urban areas if military or economic targets were located there. Most economic targets are co-located with urban areas, and many military targets, such as airfields capable of sustaining redeployed strategic aircraft, naval bases, and C²I facilities, are also co-located with urban areas. The number of economic targets not co-located with urban areas may be comparable to the number of military targets that are co-located with urban areas. Therefore, for the purpose of this study the committee has assumed that some 3,500 weapons with a yield of approximately 1,500 Mt would strike urban areas. Specifically, as a first approximation, it is assumed that economic targets and co-located military targets would be distributed in the largest 1,000 NATO/Warsaw Pact urban areas roughly in proportion to the population of those areas. As detailed in the chapter on fires resulting from such an attack, it is assumed that there would be one-third overlap of areas exposed to 20 cal/cm². These assumptions imply that fire ignition would occur over 50 percent of the areas of these cities.

The committee has assumed that both sides would fuse their warheads for air or ground burst to optimize military effectiveness against the targets under attack and not to increase population fatalities. With this in mind, it is estimated that about 25 percent (1,500 Mt) of the total yield would be ground bursts. One ground burst is assumed against each silo and other hardened target.

Given the large number and wide distribution of possible targets in this scenario, it is assumed as a first approximation that the targets and megatonnage would be distributed evenly over the land areas from latitudes 30°N to 70°N. A more precise approximation by examining the density of known major strategic targets and urban areas within these latitudes; however, such detail would not add appreciable precision to the present estimation of atmospheric consequences until knowledge about soot production, transport, and removal is much improved.

It is important to note that this weapons exchange assumes that all targets would have been chosen to have direct or indirect impact on the ability of the two sides to conduct or sustain military operations or to emerge from the hostilities in a superior position. No targets would be chosen to maximize worldwide population fatalities or long-term effects on the biosphere. Consequently, it is assumed that there would be no attacks on urban areas in countries not directly involved in the conflict. The committee has assumed that there would be no attacks solely designed to ignite or sustain forest fires -- and no attacks on oil fields, since the destruction of storage facilities and refineries would provide more immediate and effective denial of petroleum products. In addition, it is assumed that the war at sea would be directed against specific ships and submarines.

In this 6,500-Mt baseline case, no large multimegaton weapons would be employed by either side. In order to examine the atmospheric effects of very high yield explosions, the committee has also analyzed a second case -- an 8,500-Mt excursion -- in which sufficient multimegaton (i.e., 20 Mt) missile warheads would be deployed to permit successful delivery of approximately 100 such weapons on superhard, high-value targets, in addition to the 6,500-Mt baseline megatonnage. It is assumed that these would all be surface bursts.

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"Is the Nuclear Winter Modelling Credible?"

"To this question the Committee replies "yes", but advises caution. It believes that major, if temporary, climate upsets would follow nuclear war. The details provided by the models are plausible although the uncertainties are still formidable. We are impressed by the fact that several different modelling exercises have led to broadly similar conclusions supporting the likelihood that catastrophic cooling would occur.

The anticipated physical and chemical changes can be expressed as mathematical relationships, represented as equations, which may then be combined into an integrated numerical description (albeit an imperfect one) of the environment. These are called "models". They are very complex and require high-capacity computers for their solution. The models can be designed to compare the way in which the undisturbed atmosphere behaves when dust and smoke are added at specified altitudes and latitudes. Despite their complexity, the models are crude representations of reality because nature cannot be fully described by a few -- or a few hundred -- mathematical equations. Despite such limitations, simulation modelling has proven to be a powerful technique for investigating many natural phenomena, and sometimes they are the only practical means at hand.

Quantitative support for the nuclear winter hypothesis rests on a few large numerical modelling exercises. The Committee has examined these exercises, and concludes that:

The models are for the most part credible as to the broad nature of the climatic impacts that will follow a major nuclear exchange, though the details are no more than plausible.

Although the results must be interpreted with care, a prima facie case has been made that a nuclear winter will follow from nuclear explosions of a wide range of severity, including those that are considered quite small in present strategic scenarios. Every effort should be made to clear up the uncertainties that remain.

Criticisms of the models by Teller, Singer, Maddox and others make some valid points, but do not invalidate the main thrust of the model results.

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

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

The one-dimensional model has other shortfalls. Recovery from the minimum temperatures would largely be accomplished through the gradual removal of smoke and dust, and it was assumed that this removal rate would be the same in the perturbed atmosphere as it is in the normal atmosphere. Even in the normal atmosphere, removal of pollutants is a poorly understood process.

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Most pollution removal depends on atmospheric circulation and precipitation, but in an atmosphere with a very heavy burden of smoke and dust, the circulation and weather processes may be greatly altered. Some potential alterations could lead to much slower removal than normal, others to more rapid removal. Currently we have little insight into this uncertainty.

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

Substantial scavenging of smoke injected into the lower atmosphere from the continents of the Northern Hemisphere may occur as the smoke is being more widely dispersed over the hemisphere.

Lofting of smoke through solar heating could act to increase the lifetime of the remaining smoke and may reduce the sensitivity to height of injection.

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For very large smoke injections, global-scale spreading and cooling are more likely in summer than in winter.

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

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

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

We have very little confidence in the near-term ability to predict this phenomenon quantitatively, either in terms of the amount of sunlight obscured and the related temperature changes, the period of time such consequences may persist, or of the levels of nuclear attacks which might initiate such consequences. ..."

IV. FIRES AND EFFECTS OF SMOKE


"Fires

"From an atmospheric point of view, the most serious effects of a nuclear war would most likely result from the many fires which would start in the war and could not be extinguished because of nuclear contaminations and loss of water lines, fire equipment and expert personnel. The devastating effects of such fires in urban areas were indicated by Lewis. Here we show that the atmospheric effects would be especially dramatic. Several types of fires may rage. Besides the fires in urban and industrial centers, vast forest fires would start, extensive grasslands and agricultural land would burn, and it is likely that many natural gas and oil wells would be ruptured as a result of the nuclear explosions, releasing huge quantities of oil and natural gas, much of which would catch fire. To give an estimate of the possible effects, we will consider as a working hypothesis that 10^6 km^2 of forests will burn (this corresponds roughly to the combined area of Denmark, Norway
and Sweden) and that breaks in gas and oil production wells will release gaseous effluents from the earth corresponding to the current rate of worldwide usage. In our opinion these are underestimates of the real extent of fires that would occur in a major nuclear war.

Gaseous and Particulate Emissions from Forest Fires

In the US and especially in Canada and the USSR, vast forests are found close to important urban strategic centers, so that it may be expected that many wildfires would start burning during and after the nuclear exchange. Although it is hard to estimate how much forest area might burn, a total of 10^6 km^2, spread around in the Northern Hemisphere, is probably an underestimate, as it is only about 20 times larger than what is now annually consumed by wildfires. This amounts to 4 percent of the temperate and boreal forest lands, and is not larger than that of the urban areas combined. Furthermore, Ward et al. have pointed out that effective fire control and prevention programs have reduced the loss of forests in the US (exclusive of Alaska) from 1.8 x 10^5 km^2 in the early 1930s to less than 1.6 x 10^4 km^2 by the mid 1970s. The US Forest Service is quoted as estimating that a nuclear attack on the US of approximately 1,500 Mt would burn a land area of 0.4-6 x 10^6 km^2 in the US. All this information indicates that our assumption of 10^6 km^2 of forest area that could be consumed by fire is not an overestimate.

An area of 10^6 km^2 of forest contains on the average about 2.2 x 10^16 g dry matter or about 10^15 g of carbon phytomass and about 10^14 g of fixed nitrogen, not counting the material which is contained in soil organic matter. Typically, during forest wildfires about 25 percent of the available phytomass is burned, so that 2.5 x 10^15 g of carbon would be released to the atmosphere. During wildfires about 75 kg of particulate matter is produced per ton of forest material burned or 450 kg of carbon, so that 4 x 10^14 g of particulate matter is injected into the atmosphere by the forest fires. Independently, we can use the information by Ward et al. to estimate the global biomass and suspended particulate matter expected to be produced by wildfires which would be started by the nuclear war. According to these authors the forest area now burned annually in the US, excluding Alaska, is about 1.8 x 10^5 km^2, which delivers 3.5 x 10^12 g particulate matter to the atmosphere. Accordingly, a total area of 10^6 km^2 would inject 2 x 10^14 g particulate matter into the atmosphere which should come from 3 x 10^15 g of burned forest material, or 1.3 x 10^15 gC. This is a factor of 2 less than the earlier derived estimate, so we will use a range of 1.3-2.5 x 10^15 g of carbon as the global atmospheric gaseous release and 2-4 x 10^14 g as particulate matter.

In forest fires most of the carbon is released as CO_2 to the atmosphere. The forest fire contribution to the atmospheric CO_2 content, which totals 7 x 10^17 g of carbon, is rather insignificant. The repercussions of the forest fires are, however, much more important for the contribution of other gases to the atmosphere, e.g. carbon monoxide (CO). With a relative release rate ratio CO:CO_2 of about 15 percent, the production of CO would amount to 2-4 x 10^14 gC, which is roughly equal to or two times larger than the present atmospheric CO content. Within a short period of time, average concentrations of CO at midlatitudes in the Northern Hemisphere would increase by up to a factor of four, and much larger

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CO increases may be expected on the continents, especially in regions downwind (generally east of the fires). Accompanying those emissions there will also be significant inputs of tens of Teragrams (1 Teragram = 1 Tg = 10^{12}g) of reactive hydrocarbons to the atmosphere, mostly ethylene (C_2H_4) and propylene (C_3H_6), which are important ingredients in urban, photochemical smog formation. More important, phytomass consists roughly of about 1 percent fixed nitrogen, which is mainly contained in the smaller-sized material such as leaves, bark, twigs and small branches, which are preferentially burned during fires. As a rough estimate, because of the forest fires we may expect an input of 15-30 Tg of nitrogen into the atmosphere. Such an emission of NO would be larger than the production in the nuclear fireballs and comparable to the entire annual input of NO\textsubscript{x} by industrial processes. Considering the critical role of NO in the production of tropospheric ozone, it is conceivable that a large accumulation of ozone in the troposphere, leading to global photochemical smog conditions, may take place. An increase of ozone due to photochemical processes in forest fire plumes has indeed been observed by several investigators.

Particulate Matter from Forest Fires and Screening of Sunlight

The total production of 2-4 \times 10^{14}g of particulate matter from the burning of 10^6 km\textsuperscript{2} of forests is comparable on a volume basis to the total global production of particulate matter with diameter less than 3 microns (\mu m) over an entire year (or 200-400 million tons). The physical and chemical nature of this material has been reviewed.

The bulk of the mass (more than 90 percent) of the particulate matter from forest fires consists of particles with diameters of less than 1 \mu m and a maximum particle number density at a diameter of 0.1 \mu m. The material has a very high organic matter content (40-75 percent) and much of it is formed from gaseous organic precursors. Its composition is on the average: 55 percent tar, 25 percent soot and 20 percent ash. These particles strongly absorb sunlight and infrared radiation. The light extinction coefficient, \( b_\text{s}(m) \), is related to the smoke density, \( d \ (g/m^3) \), by the relationship \( b_\text{s} = ad \), where a is approximately 4-9 m\textsuperscript{2}/g. With most smoke particles in the submicron size range, their average residence time in the atmosphere is about 5-10 days. If we assume that the forest fires will last for two months, a spread of 2-4 \times 10^{14}g of aerosol over half of the Northern Hemisphere will cause an average particle loading such that the integrated vertical column of particles is equal to 0.1-0.5g/m\textsuperscript{2}. As a result, the average sunlight penetration to the ground will be reduced by a factor between 2 and 150 at noontime in the summer. This would imply that much of the Northern Hemisphere would be darkened in the daytime for an extended period of time following the nuclear exchange. The large-scale atmospheric effects of massive forest fires have been documented in a number of papers. Big forest fires in arctic regions are commonly accompanied by huge fires in peat bogs, which may burn over two meters in depth without any possibility of being extinguished. The production of aerosol by such fires has not been included in the above estimates.

Gas, Oil and Urban Fires

In addition to the above mentioned fires there are also the effects of fires in cities and industrial centers, where huge quantities of combustible materials and chemicals are stored. As an example, if the European 95-day energy stockpile
is roughly representative for the world, about $1.5 \times 10^{15}$ gC fossil fuel (around 1.5 thousand million tons) is stored globally. Much of this would be destroyed in the event of a nuclear war. Therefore, if the relative emission yields of particulate matter by oil and gas fires are about equal to those of forest fires, similar rates of production of atmospheric aerosol would result. Although it may be enormously important in this study we will not consider the global environmental impacts of the burning and release of chemicals from urban and industrial fires, as we do not yet have enough information available to discuss this matter in a quantitative manner.

Even more serious atmospheric consequences are possible, due to the many fires which would start when oil and gas production wells are destroyed, being among the principal targets included in the main scenario provided for this study. Large quantities of oil and gas which are now contained under high pressure would then flow up to the earth's surface or escape into the atmosphere, accompanied by huge fires. Of course, it is not possible for the nuclear powers to target all of the more than 600,000 gas and oil wells of the world. However, certain regions of the world where production is both large and concentrated in small areas are likely to be prime targets in a nuclear war. Furthermore, the blowout of a natural gas well results in the release of gas at a much greater rate than is allowed when under control and in a production network. For example, one of the more famous blowouts, "The Devil's Cigarette Lighter", occurred at Gassi Touil in the Sahara. This well released $15 \times 10^6$ m$^3$ of gas per day until the 200-meter high flame was finally extinguished by explosives and the well capped. Fewer than 300 such blowouts would be required to release natural gas (partly burned) to the atmosphere at a rate equal to present consumption. Descriptions of other blowouts such as the Ekofisk Bravo oil platform in the North Sea, a sour gas well (27 percent H$_2$S) in the province of Alberta, Canada and the Ixtoc I oil well in the Gulf of Mexico may be found in the literature.

As an example of how very few weapons could be used to release large quantities of natural gas, consider the gas fields of the Netherlands. The 1980 production of $7.9 \times 10^4$ m$^3$ of natural gas in Groningen amounted to 38 percent of that for all of Western Europe and 5 percent of that for the entire world. Most of the gas production in the Netherlands is concentrated in a field of about 700 km$^2$ area. It seems likely that a 300-kt nuclear burst would uncap every gas well within a radius of 1 km either by melting the metal pipes and valves, by snapping the pipes off at the ground by the shock wave, or by breaking the well casings via shock waves propagated in the earth. This is in consideration of the following facts: 1) the fireball radius is 0.9 km, 2) for a surface burst the crater formed is approximately 50 m deep and 270 m in diameter, 3) the maximum overpressure at 1 km is 3.1 atmospheres (atm), 4) the maximum dynamic pressure at 1 km is 3.4 atm, and 5) the maximum wind speed at 1 km is 1700 km/h. Considering then that a 300-kt bomb has a cross-section of greater than 3 km$^2$ for opening gas wells, fewer than 230 such weapons are required to cover the entire 700 km$^2$ Groningen field of the Netherlands. This amounts to less than 69 Mt of the 5750 Mt available for the Scenario I nuclear war.

Offshore oil and gas platforms might also be targets of a nuclear war. For example, in 1980 the United Kingdom and Norway produced $2.1 \times 10^6$ barrels of oil per day from a total of 390 wells (about 40 platforms) in the North Sea.
Considering that a 100-kiloton weapon would be more than sufficient to destroy an offshore platform, only 4 Mt of explosive yield need be used to uncap these wells, which produce 3.5 percent of the world's petroleum.

One can point out many other regions of the world where gas and oil production is particularly concentrated. Production in the US is considerably more dispersed than in other countries, however. For comparison, in 1980 the US produced an average of $8.6 \times 10^6$ barrels of oil per day from about 530,000 wells whereas the USSR production was $12.1 \times 10^6$ barrels per day from only 80,000 wells. The oil and gas fields of the Soviet Union, particularly the oil producing Volga-Ural region and the gas and oil fields of the Ob region, are highly localized and particularly vulnerable to nuclear attack.

Much of the gas and oil released as a result of nuclear attacks will burn. This is another source of copious amounts of particulate matter in the atmosphere. However, it is also likely that a fraction of the gas would escape unburned to the atmosphere where it would be gradually broken by photochemical reactions. Much of the escaping oil may likewise burn, but an appreciable portion of it may volatilize as in the Ixtoc I blowout in the Gulf of Mexico, which resulted in the world's largest oil spill. In this case it is estimated that only 1 percent of the oil burned, while 50-70 percent evaporated. We next consider the influence of these emissions on the gaseous composition of the atmosphere.

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Of course it is impossible to guess how many oil and gas well destructions would result from a nuclear war, how much gas will burn and how much will escape unburned to the atmosphere. As an example to indicate the atmospheric effects, let us assume that quantities of oil and gas will continue to burn corresponding to present usage rates, with 25 percent of the present production gas escaping unburned into the atmosphere. We do not know whether the latter assumption is realistic. If not, the chosen conditions may represent a gross underestimate of the atmospheric emissions which could take place during and after a nuclear war. This is, of course, especially the case when the world's oil and gas production fields are targeted as foreseen in the main scenario of this study. We simulate NOx emissions from oil and gas field fires with those provided by current industrial rates. This adds 20 Tg of nitrogen to the NOx source from forest fires.

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

Simulations

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

In the baseline scenario (case 1, 5,000 MT), the initial NH optical depth is approximately 4, of which approximately 1 is due to stratospheric dust and approximately 3 to tropospheric smoke. After 1 month the optical depth is still approximately 2. Beyond 2 to 3 months, dust dominates the optical effects, as the soot is largely depleted by rain-out and wash-out. In the baseline case, about 240,000 km$^2$ of urban area is partially (50 percent) burned by approximately 1,000 MT of explosions (only 20 percent of the total exchange yield). This roughly corresponds to one sixth of the world's urbanized land area, one fourth of the developed area of urban centers with populations greater than 100,000 in the NATO and Warsaw Pact countries. The mean quantity of combustible material consumed over the burned area is approximately 1.9 g/cm$^2$. Wildfires ignited by the remaining 4,000 MT of yield burn another 500,000 km$^2$ of forest, brush, and grasslands, consuming approximately 0.5 g/cm$^2$ of fuel in the process.

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

The optical depth simulations for cases 1, 2, 9, and 10 in Fig. 1 show that a range of exchanges between 3,000 and 10,000 MT might create similar effects. Even cases 11, 12, and 13, while less severe in their absolute impact, produce optical depths comparable to or exceeding those of a major volcanic eruption. It is noteworthy that eruptions such as Tambora in 1815 may have produced significant climate perturbations, even with an average surface temperature decrease of less than or approximately 1 K.
Case 14 represents a 100-MT attack on cities with 1,000 100-KT warheads. In the attack, 25,000 km² of built-up urban area is burned (such an area could be accounted for by approximately 100 major cities). The smoke emission is computed with fire parameters that differ from the baseline case. The average burden of combustible material in city centers is 20 g/cm² (versus 10 g/cm² in case 1) and the average smoke emission factor is 0.026 gram of smoke per gram of material burned (versus the conservative figure of 0.011 g/g adopted for central city fires in the baseline case). About 130 million tons of urban smoke is injected into the troposphere in each case (none reaches the stratosphere in case 14). In the baseline case, only about 10 percent of the urban smoke originates from fires in city centers.

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

"A nuclear explosion can readily ignite fires in either an urban or a rural setting. The flash of thermal radiation from the nuclear explosion, which has a spectrum similar to that of sunlight, accounts for about a third of the total energy yield of the explosion. The flash is so intense that a variety of combustible materials are ignited spontaneously at ranges of 10 kilometers or more from a one-megaton air burst detonated at a nominal altitude of a kilometer. The blast wave from the explosion would extinguish many of the initial fires, but it would also start numerous secondary fires by disrupting open flames, rupturing gas lines and fuel storage tanks and causing electrical and mechanical sparks. The destruction resulting from the blast wave would also hamper effective fire fighting and so promote the spread of both the primary and secondary fires. Based on the known incendiary effects of the nuclear explosions over Hiroshima and Nagasaki in 1945 it can be projected that the fires likely to be caused by just one of the far more powerful strategic nuclear weapons available today would extend over an area of from tens to hundreds of square kilometers.

Nuclear explosions over forests and grasslands could also ignite large fires, but this situation is more difficult to evaluate. Among the factors that affect fires in wilderness areas are the humidity, the moisture content of the fuel, the amount of the fuel and the velocity of the wind. Roughly a third of the land area in the North Temperate Zone is covered by forest, and an equal area is covered by
brush and grassland. Violent wildfires have been known to spread over tens of thousands of square kilometers from a few ignition points; in the absence of a nuclear war such fires occur about once every decade. Although most wildfires generated by nuclear explosions would probably be confined to the immediate area exposed to the intense thermal flash, it is possible that much larger ones would be started by multiple explosions over scattered military targets such as missile silos.

The total amount of smoke likely to be generated by a nuclear war depends on, among other things, the total yield of the nuclear weapons exploded over each type of target, the efficiency of the explosions in igniting fires, the average area ignited per megaton of yield, the average amount of combustible material in the irradiated region, the fraction of the combustible material consumed by the fires, the ratio of the amount of smoke produced to the amount of fuel burned and the fraction of the smoke that is eventually entrained into the global atmospheric circulation after local rainfall has removed its share. By assigning the most likely values to these parameters for a nuclear war involving less than 40 percent of the strategic arsenals of the two superpowers, we were able to calculate that the total smoke emission from a full-scale nuclear exchange could easily exceed 100 million metric tons. In many respects this is a conservative estimate. Crutzen and his co-workers Ian Galbally of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia and Christoph Bruhl of the Max Planck Institute at Mainz have recently estimated that the total smoke emission from a full-scale nuclear war would be closer to 300 million tons.

One hundred million tons of smoke, if it were distributed as a uniform cloud over the entire globe, could reduce the intensity of sunlight reaching the ground by as much as 95 percent. The initial clouds would not cover the entire globe, however, and so large areas of the Northern Hemisphere, particularly the target zones, would be even darker; at noon the light level in these areas could be as low as that of a moonlit night. Daytime darkness in this range, if it persisted for weeks or months, would trigger a climatic catastrophe. Indeed, significant disturbances might be caused by much smaller amounts of smoke.

Wildfires normally inject smoke into the lower atmosphere to an altitude of five or six kilometers. In contrast, large urban fires have been known to inject smoke into the upper troposphere, probably as high as 12 kilometers. The unprecedented scale of the fires likely to be ignited by large nuclear explosions and the complex convective activity generated by multiple explosions might cause some of the smoke to rise even higher. Studies of the dynamics of very large fires suggest that individual smoke plumes might reach as high as 20 kilometers, well into the stratosphere.

During the World War II bombing of Hamburg the center of the city was gutted by an intense firestorm, with heat-generated winds of hurricane force sweeping inward from all directions at ground level. Rapid heat release over a large area can create fire vortexes, heat tornadoes and cyclones with towering convective columns. The sheer intensity of such fires might act to reduce the smoke emission considerably through two processes: the oxidation of carbonaceous smoke particles at the extremely high temperatures generated in the fire zone and the washout of smoke particles by precipitation formed in the convective column. Both effects were taken into account in our estimates of the total smoke emission from a nuclear war.
The climatic impact of smoke depends on its optical properties, which in turn are sensitive to the size, shape and composition of the smoke particles. The most effective light-screening smoke consists of particles with a radius of about 1 micrometer and a very sooty composition rich in graphite. The least effective smoke in attenuating sunlight consists of particles larger than 0.5 micrometer with a predominantly oily composition. The smoke from a forest fire is typically composed of extremely fine oily particles, whereas the smoke from an urban fire consists of larger agglomerations of sooty particles. Smoke from fierce fires usually contains large particles of ash, char, dust and other debris, which is swept up by the heat-generated winds. The largest of these particles fall out of the smoke clouds just downwind of the fire. Although very intense fires produce less smoke, they lift more fine dust and may burn metals such as aluminium and chromium, which efficiently generate fine aerosols.

The release of toxic compounds in urban fires has not been adequately studied. It is well known that many people who have died in accidental fires have been poisoned by toxic gases. In addition to carbon monoxide, which is produced copiously in many fires, hydrogen cyanide and hydrogen chloride are generated when the synthetic compounds in modern building materials and furnishings burn. If large stores of organic chemicals are released and burned in a nuclear conflict, additional airborne toxins would be generated. The possibility that vast areas could be contaminated by such pyrotoxins, absorbed on the surface of smoke, ash and dust particles and carried great distances by winds, needs further investigation.

* * *


"Urban Ignition"

"Some evidence that nuclear explosions are unique in their ability to ignite mass fires is offered by the Hiroshima and Nagasaki experiences. One crude estimate of the average energy release rate places the Hiroshima fire among the least intense of the mass fires of World War II (Martin, 1974). Nevertheless, centripetal winds characteristic of a firestorm apparently developed, and the fuel consumption within the fire zone was nearly complete (GD77; Ishikawa and Swain, 1981).

... Even though the blast wave that follows the thermal pulse could extinguish many of the primary thermal radiation fires, a substantial number of these ignitions would continue to burn. Idealized field tests to determine the efficiency of fire extinction by pressure waves are contradictory, and often little or no effect is observed (Wiersma and Martin, 1973; OTA, 1979; Backovsky et al., 1982). In fact, in one study, the blast dispersal of burning curtain fragments through a room was a major factor in fire development (Goodale, 1971). In addition, the blast ignites many secondary fires and creates conditions ... that strongly favor the growth and spread of the surviving fires. Overall, blast would appear to
encourage mass fire development. The evidence from Hiroshima and Nagasaki suggests that both primary and secondary fires eventually contributed to the conflagrations.

Detailed models of nuclear fire initiation and spread in urban and suburban settings have been constructed (Miller et al., 1970; Martin, 1974; FEMA, 1982), although their fidelity is in some doubt (Miller et al., 1970). The models suggest that, within the 20-cal/cm² irradiation perimeter, more than or of the order of 20 percent of the buildings could have one or more initial fires. This assumes that the blast wave extinguishes almost all of the primary fires and, overall, inhibits fire growth and spread (FEMA, 1982). However, even if the initial fires are sparsely distributed after a nuclear explosion, nearly all blocks of houses or buildings are likely to have at least one fire (Martin, 1974). By implication, few effective firebreaks would exist in the initial fire zone. Observations of everyday urban fires indicate that fire spread between buildings (mainly by heat radiation and firebrands) is very efficient (of the order of 50 percent probability) at separations of about 7 m or less, and can occur over distances of 15 or 30 m (Chandler et al., 1963; Ayers, 1965; FEMA, 1982). Rows of residential homes, and certainly buildings in city blocks, are generally separated by less than 10 m. Accordingly, there is a high probability that 50 percent or more of these buildings would eventually burn out (Martin, 1974; FEMA, 1982). Owing to the dispersal of fuel by the blast into the gaps between the buildings, and the strong winds generated by the explosions and conflagrations, fire spread could be even more efficient in the nuclear case. Large isolated (industrial) buildings would also have a high probability of burning because of their large total area of exposure and therefore high likelihood of having at least one initial fire (Martin, 1974).

At blast overpressures of more than or of the order of 15 psi, concrete and steel buildings suffer severe damage and break apart to produce rubble. The area of such damage is about 25 km²/Mt (GD77). In densely built up areas, the rubble could be several meters deep. Fires can burn in rubble, but generally at a slower rate. Obviously, civil defense and firefighting efforts would be futile under such conditions, and fire spread would be uninhibited by gaps and open areas. The buried fuels would tend to smolder and pyrolyze in the heated air that filtered through the rubble, thus smoking copiously. It is expected that a large fraction of the combustibles in the rubblized zone would eventually burn, possibly with an exaggerated smoke emission confined to lower altitudes.

If an effective firefighting effort could be mounted, many of the initial urban fires might be extinguished and fire spread substantially limited in the lower over pressure regions (Kanury, 1976; FEMA, 1982). Such an expectation is probably optimistic. In Hiroshima and Nagasaki, even under wartime preparedness, firefighting efforts were largely futile (Ishikawa and Swain, 1981). Once the initial fires had grown to even moderate size, attempts at containment were hopeless without sufficient water, tools, and manpower. It follows that, within 1 to 2 h after a nuclear explosion over a city, major fires would be burning throughout the original fire ignition zone.

Forest Ignition

Little information is available on forest, brush, and grass fires initiated by nuclear explosions (Jaycor, 1980). Some factors that would influence the extent of nuclear wildfires are as follows:
1. The number of low air bursts over areas of forest, brush, and grass.

2. Meteorological conditions, such as cloudiness, precipitation, winds, humidity, and snow cover.

3. The probability of igniting persistent fires in the fuel bed, accounting for the shading of dry fuels by the live canopy.

4. The probability of fire spread in the fuel bed.

5. The effects of blast on the distribution of fuels and the development of fires.

6. Other factors, such as terrain, existence of firebreaks, and nearby nuclear explosions.

Rough estimates for some of these factors, based on past wildfire experience and theoretical analyses of nuclear effects, are discussed below.

Although Ayers (1965) had pointed out that many fires are likely to occur in a nuclear exchange, Crutzen and Birks (1982) made the first quantitative estimate of forest fire smoke and gas emissions in a nuclear war, and proposed that large quantities might be generated. As in cities, the nuclear bomb light is likely to ignite numerous small fires over a large area, most of which would be extinguished by the blast wave (Jaycor, 1980). The area initially subject to ignition could be as large as 500 km²/Mt (Ayers, 1965), which corresponds to thermal fluences of more than or of the order of 10 cal/cm². It is possible that the number of individual fires surviving the blast wave and developing into major conflagrations could well exceed one per 10,000 m² (i.e., 100 ignitions per square kilometer). The rise of the nuclear fireball would establish strong afterwinds to fan the fires. It is unlikely that organized firefighting crews with sophisticated equipment would be available to extinguish the flames.

Nuclear forest fires would not resemble most forest fires of the past. It is conceivable, although uncertain, that, because of the simultaneous ignition over a large area and the fanning action of the afterwinds, some of the nuclear forest fires could develop into intense firestorms with towering smoke plumes. The distribution and consumption of fuel in nuclear forest fires could also be significantly modified. For one thing, much of the forest canopy and some heavy timbers would be shattered and blown down into the burning zone. If the nuclear fire were very intense, even large standing timbers could be substantially charred. Thus nuclear forest fires might consume a larger fraction of the forest fuels than typical natural wildfires.

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Finally, the net smoke emission factor is assumed to be 0.02 g/g (grams of smoke per gram of fuel consumed) after scavenging and removal by coagulation and condensation processes in the convective fire plumes is taken into account (50 percent removed). Multiplying the appropriate factors together, the total urban smoke emission amounts to approximately equal to 150 Tg (1.5 x 10¹⁴ g).
Forest fires are also estimated to burn 250,000 km\(^2\) (i.e., roughly the area of irradiation at more than or of the order of 20 cal/cm\(^2\) by 1,000 Mt of air bursts). The basis for this estimate is discussed earlier in this chapter. The fuel consumed in forest fires is taken to be 0.4 g/cm\(^2\) (about 20 percent of the typical fuel loading), and the net smoke emission factor is taken to be 0.03 g/g, both values based on observations. Brush and grass fires, whose emissions are smaller per unit area burned, are not explicitly included in the analysis. The total forest fire smoke emission is then approximately equal to 30 Tg. In winter, wildfire emissions might be reduced to a few teragrams; however, because urban fires contribute much more soot, the total emission would be reduced by no more than 20 percent.

The composition and optical properties of the smoke in the baseline model must also be specified. Even though urban fires dominate the aggregate smoke emission in the baseline case, with potential soot fractions of up to 90 percent, it is assumed that graphitic carbon fraction is only 20 percent (compared to of the order of 10 percent in forest fire smoke). The smoke particle number size distribution is taken to be log normal with a number mode radius* of 0.1 \(\mu\)m and \(\gamma = 2.0\); the effective particle density is 1 g/cm\(^3\). The smoke infrared extinction and absorption coefficients (at 10 \(\mu\)m) are both roughly 0.5 m\(^2\)/g. These physical constants provide a consistent set for optical (Mie) calculations.

Because the selected baseline optical extinction and absorption coefficients are much smaller than typical values for sooty (urban) smokes, the effect of "aging," which can reduce the optical efficiency of the smoke, may be neglected in carrying out approximate optical-effects simulations. The optical efficiency is otherwise expected to decline in time.

... The total estimated smoke emission is 180 Tg, caused by roughly 30 percent of the nuclear explosions. The estimated smoke emissions are very uncertain, however; some of the sources of uncertainty are discussed below.

The total quantity of combustibles consumed in the baseline war scenario is 8,500 Tg (7,500 Tg in urban fires and 1,000 Tg in forest fires). For the urban flammables, about 5,000 Tg of cellulosics, 1,500 Tg of liquid fossil organics, and 1,000 Tg of industrial organochemicals, plastics, polymers, rubbers, resins, etc., are burned. The corresponding total energy release is about 5 \(\times 10^{19}\) cal, or 50,000 Mt, assuming an average heat of combustion of 6,000 cal/g. (Note, by comparison, that one day's solar insolation amounts to about 3,000,000 Mt of energy.) The energy release drives the buoyancy of the fire plumes and may create strong surface winds. Because the initial nuclear detonations over cities would pulverize large quantities of masonry and plaster into fine dust, it is likely that a significant burden of submicron particulates would be drawn up into the fire plumes. Even if 1,000 tons of fine (submicron) dust were raised for each megaton of thermal energy released, the dust injection could total 30 Tg. However, because there are few data pertaining to this source of particulates, it is ignored in the baseline assessment; future consideration seems worthwhile.

* For volume-equivalent spherical particles.
/...
As was discussed earlier, the smoke mass insertion is assumed to be uniform with height between the ground and 9-km altitude, and to occur over a period of several days to 1 week.

Excursions from the Baseline Case

In order to place some limits on the possible range of smoke emissions in the baseline scenario, reasonable excursions of the fire parameters are investigated. These excursions are not meant to represent an absolute range of possibilities, but a range that seems to be consistent with current scientific knowledge. In the case of urban fires, the area burned is varied between 25 percent and 75 percent of the urbanized area of the NATO and Warsaw Pact countries (neglecting possible urban damage in other industrialized nations such as China and Japan), the net smoke emission factor is varied between 0.01 g/g and 0.04 g/g, and the fuel burden is varied between 2 g/cm² and 4 g/cm². None of these assumptions appears to be extreme. The resulting urban smoke emission varies from approximately equal to 20 Tg to approximately equal to 450 Tg. This range of emissions is in rough accord with the range estimated by Broyles (1984). In the case of forest fires, it is assumed, on the low side, that no smoke emissions would occur. On the high side, a fourfold increase in the burned area and a smoke emission factor of 0.05 g/g are assumed, yielding a forest smoke emission of approximately equal to 200 Tg. Accordingly, the present estimate of a potential range of smoke emissions following the baseline nuclear exchange is approximately equal to 20 to approximately equal to 650 Tg. This is not an uncertainty range for the emission, but an excursion range based on plausible parameter variations. Sources of uncertainty in these estimates are discussed in the next section.

Because it is possible that the smoke plumes of massive urban fires would penetrate into the stratosphere, it is worthwhile to consider the implications of smoke injections in the lower stratosphere. The injection of up to 10 Tg of smoke (just over 5 percent of the baseline calculation), it represents a potentially interesting excursion (Turco et al., 1983a, b).

Turco et al. (1983a, b) pointed out that massive smoke emissions would be possible in nuclear exchanges that involved only a limited total yield detonated over or near major urban centers. This conclusion is based on the observation that most urban areas tend to have dense "cores" in which combustible materials are concentrated. Thus about 100 Mt (say, in 50- and 100-kt weapons) would be sufficient to attack all of the major urban centers in the NATO and Warsaw Pact countries. Such a purposefully destructive strategy is currently thought to be unlikely. However, an equivalent result is possible. For a scenario of any size in which 100 Mt of explosions were to burn an urban area of 25,000 km² (about 50 percent of the city cores of the combatant nations), consume 20 g/cm² of combustibles, and emit 2 percent (net) of the burned mass as particulate in the process, approximately equal to 100 Tg of smoke would be generated. This is similar to the baseline urban smoke emission of 150 Tg. However, the emission would be patchier for a longer time in the 100-Mt case due to a reduced number of smoke sources.
In accordance with the estimates presented above, one may deduce that smoke emissions from nuclear-initiated wildfires scale very roughly with the total yield of the exchange, including tactical weapons, and are very sensitive to season, with maximum emissions in summer and early fall and minimum emissions in winter. Smoke production by urban fires, on the other hand, may be rather insensitive to total yield, if the urban centers, or the military and industrial sites within urban zones, are systematically targeted. The effect of seasonal and meteorological conditions on nuclear urban fires (as with everyday urban fires) is also less important, owing to the general protection of urban combustibles from the weather.

Uncertainties

Uncertainties are recognized in each of the key parameters pertaining to fires and smoke emissions in a nuclear war. Although only very rough estimates of the uncertainties may be deduced, even these may be useful in evaluating the weaknesses in current knowledge. Accordingly, a subjective assessment of uncertainties, based on consideration of the limited set of data available to the committee, is spelled out below.

1. The areal extent of nuclear urban fires per megaton of yield (factor of 2 to 3). Potential overlap of fire zones, and fire spread, dominates the uncertainty.

2. Quantities and distributions of flammable materials in cities and surrounding areas (factor of 3 in the average central-city fuel burden, factor of 2 in the average suburban fuel burden, factor of 3 in the worldwide urban-area average fuel burden).

3. Urban smoke emissions per unit mass of combustible loading (factor of 2 in the fraction of fuel burned in urban nuclear fires, factor of 2 to 3 in the quantity, or mass, of smoke generated per unit mass of material burned, factor of 3 in the graphitic carbon mass in the average particle bulk density).

4. Optical (visible wavelength) properties of urban fire smoke (factor of 2 in the specific extinction and scattering coefficients (square meters per gram), factor of 3 in the specific absorption coefficient (square meters per gram), factor of 3 in the imaginary part of the refractive index).

5. Infrared properties of urban fire smoke (factor of 3 in the late-time specific extinction/absorption coefficient which may be controlled by condensed water and fly ash).

6. The areal extent of nuclear forest fires (factor of 3 to 4, neglecting sensitivity to the explosion scenario).

7. Forest fire smoke emissions per unit area burned (factor of 2 to 3 in the fraction of biomass fuel consumed, factor of 2 in the mass of smoke emitted per unit mass of fuel burned, factor of 3 in the size, and factor of 1.5 in the average particle bulk density).
8. Optical (visible wavelength) properties of forest fire smoke (factor of 1.5 to 2 in the specific extinction and scattering coefficients (square meters per gram), factor of 3 in the specific absorption coefficient (square meters per gram), factor of 3 in the imaginary part of the refractive index).

9. Infrared properties of forest fire smoke (factor of 2 to 3 in the specific extinction/absorption coefficient at intermediate and late times).

10. Heights of smoke plumes from mass nuclear urban and forest fires (factor of 1.5 to 2 in both cases).

11. Extent of precipitation scavenging (black rain) and coagulation in the most intense fire plumes (the overall precipitation scavenging efficiency could vary from 25 to 75 percent; the reduction of the optical extinction and absorption coefficients by prompt coagulation in the densest plumes could vary from 20 to 50 percent).

12. Quantity of submicron masonry dust raised in urban fire plumes following polarization of buildings by nuclear blast (injection of 0 to 10^5 tons/Mt of explosive yield); the extent of smoke production from burning aluminium and other "non-flammable" materials in very intense fires is unknown.

13. Effect of massive smoke emissions on the subsequent meteorology and particle removal rates (factor of 3 to 10; see Chapter 7).

The uncertainty factors defined above cannot simply be multiplied to estimate absolute ranges of equally likely values for composite parameters such as smoke emissions and optical depths. The factors do not correspond to intervals of statistical significance, in which the central (or baseline) values are the most probable values. Because the various smoke parameters are largely uncorrelated, the uncertainty in combinations of the parameters must be deduced by statistical means. A precise determination of the overall uncertainty in the smoke emission and optical depth estimates cannot be made at this time, because the nature of the statistical dispersion has not yet been ascertained.

The propagation of uncertainty into the radiative transfer and climate calculations has an exponential component, because those calculations involve terms of the form, e^(-T). Using the present baseline case as a reference, an increase in the smoke emissions would have less impact than a decrease, inasmuch as the light absorption by the smoke is already about 90 percent, averaged over the northern hemisphere. The duration of significant effects would be prolonged, however. Patchiness, or light leakage through "holes" in the smoke clouds, also has an exponential dependence. Nevertheless, average smoke optical depths of even -1 would still imply major perturbations of the postwar environment (for example, volcanic scattering optical depths -1 can produce significant climate anomalies). The climatic aspect of the light transmission problem are discussed in Chapter 7.

Turco et al. (1983a, b) carried out a large number of sensitivity tests in which the physical parameters of smoke and dust and the explosion scenarios were varied to investigate the nature of the uncertainty in the smoke emission, light transmission, and climate variation. They concluded that as many uncertain factors could act to aggravate the effects as could act to ameliorate them.
Summary

A full-scale nuclear exchange of 6,500 Mt, involving a variety of military and urban targets, would ignite numerous fires and could generate as much as 180 Tg of smoke. Considering the substantial uncertainties involved in estimating the smoke emission, however, the plausible range of emissions extends from 20 to 650 Tg. The optical properties of the dispersed smoke clouds have been deduced principally from observational data. At visible wavelengths, a specific extinction coefficient of 5.5 M$^2$/g and a specific absorption coefficient of 2.0 M$^2$/g are selected from optical climate calculations. The infrared extinction coefficient is an order of magnitude smaller than the visible extinction coefficient. The baseline optical absorptivity is conservative (on the low side), in view of the strong absorption of light by typical sooty smokes. Even so, the implied disturbances in solar transmission on a global scale appear to be serious.

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"Fires and Forest Destruction

Much of Canada between the latitudes 50-65 degrees N is dominated by the pine, spruce, fir, and tamarack of the Boreal Forest. To the south there are large areas of mixed deciduous hardwoods contiguous with those of the adjacent U.S. From its southern border, north to the treeline and Hudson's Bay lowlands, and from east to west, Canada bears approximately 4.2 million square kilometres of forest, and contains about 80 billion tonnes of potentially combustible carbon. The species of the Boreal Forest are rich in resin and therefore particularly flammable. In summer, under normal conditions, most of this is at risk from fire. It is a reasonable assumption that a direct attack on Canadian territory, interceptions in Canadian airspace, or missile shortfalls, if occurring in summer, would start fires. The extent, and seriousness would depend upon:

- season
- fire indices pertaining at the time
- size of the attack
- quantities of timber killed by the combined effects of radiation, blast, pests and cold

In addition to these uncertainties, there is ignorance about the processes of ignition and propagation of fires by nuclear detonations. At present it is not possible to quantify with any certainty the amount of forest that would burn, but it has been suggested that if 50 Mt were detonated over the forested regions, burns in the order of 13,000-500,000 square kilometres could be expected (Turco et al., 1983).

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These are estimates for fires that start as a direct and immediate consequence of the attack. In addition, there is the possibility that the long-term fire danger would also be increased. Many trees would be killed by blast, radiation, cold (if the attack took place when the trees were in sap, before frost hardening), and pests, leaving vast quantities of flammable litter.

Coniferous trees, such as those dominating the Boreal Forest, are extremely sensitive to radiation, a lethal dose being in the general range 350-600 rads (the same order as humans). This has been known since the classic Brookhaven studies of the early 1960s (see Woodwell, 1963), and its relevance to Canada is beyond dispute.

There are various estimates of the area of forest that might be affected, and obviously the number and nature of detonations and the weather patterns are decisive variables in the assessment. One of our consultants (Grover, see Paper 7 in the Supplement) suggests that "doses exceeding several tens to several hundreds of rads would likely be found over large regions of Canada, even if a nuclear war involved only U.S. targets", although these values may be the result of long-term exposures. The possible death of forests from the combined effects of radiation and fires has three aspects of importance:

- the perturbation of a major biome, covering about 9 million square kilometers of North America (it is reasonable to suppose that commensurate damage will occur to the Siberian forests) will have global environmental consequences
- the fires will contribute smoke and soot to the atmosphere, reinforcing the climate perturbation
- the loss of trees will result in erosion of the thin and discontinuous soils of the Pre-Cambrian shield further constraining the already limited productivity
- there would be mineral and nutrient loss from the soils and major alterations to the hydrological regime
- a major economic resource would be harmed.

The severity of the potential impact, the manifest uncertainties over how fires would start and propagate, coupled with the need to find out more about the generation, distribution and properties of smoke make a convincing argument for further research on the effect of nuclear warfare on Canada's forests, and the consequent effect of forest destruction on climate.

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"In 1983 Soviet scientists published a number of papers devoted to the elaboration of the nuclear winter hypothesis.

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Smoke, soot and especially such products of city fires can virtually bar energy from reaching the surface of the Earth. As a result, solar radiation is absorbed solely by the atmosphere. In this case, the surface is warmed by thermal emission of the atmosphere, not by solar radiation. The temperature of the surface drops by tens of degrees centigrade, coming close to the temperature of the aerosol layer which has absorbed the solar radiation. As a consequence, the greenhouse effect becomes disabled, leading to nuclear night and nuclear winter.

Smoke warmed by the Sun spreads upwards and sideways from the sources of the fire. In about one month, a huge cloud of smoke and dust may envelope the northern hemisphere and begin spreading into the southern hemisphere. Over the oceans the smoke cloud perceptibly raises the temperature of the lower layers of air. Smoky atmosphere over the oceans absorbs both solar radiation and heat emission of a cooling ocean, and thus has its temperature raised even more.

Such contrasting temperatures between ocean and land produce a situation well known to meteorologists: winter monsoon of the dry season in southern and south-east Asia. City and forest fires will proceed for about a week, and in one month a dense cloud of microscopic particles of smoke and dust will cover both hemispheres. Land temperatures in the interior of the continents, even in the tropical belt, will go down to 0°C.

Pollution by forest fires

Some additional information on natural fires is given below. Russian chronicles contain data on large fires in northern Russia beginning in the year 1092. According to The Nikon's Chronicle, during huge forest fires in 1371, a person standing in the thick smoke that lasted for two months could see spots on the Sun with an unaided eye. Not only woods but dried swamps were also burning. Wild animals, having lost their scent, wandered among people; birds lost their orientation and fell to the ground. Arkhangelsk province was afflicted by a storm of forest fires during the entire summer of 1881; smoke spread over Arkhangelsk and hampered breathing. During giant fires in Siberia in 1915, an area of 120,000 km² was scorched. Because of heavy smoke the cereals ripened two weeks late, giving small, puny grain. In some places the smoke shroud was so thick that buildings five to six steps away could not be seen.

Large fires (covering more than 200 hectares) bring the greatest losses to the forest; they last for a long time, take on the dimensions of natural disasters and are extinguished mainly by natural precipitation. According to visual estimates, the smoke layer (with an eroded upper boundary) attains a height above the ground of approximately 3.5 km, and reduces the visibility at the atmospheric boundary layer to about 500 m.

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The smoke plumes from recently initiated small fires are 10–100 km in length. More extensive old fires have plumes of up to 200 km. During mass fires, according to satellite observations, smoke plumes can reach up to 300–400 km. At some distance from the fires the plumes coalesce forming a single, ribbon-shaped cloud.

We may note that the most common height of smoke plumes rising from large forest fires is 2–3 km; greater heights are rather rare. This can probably be explained by the fact that fires usually take place in dry weather and as a rule are connected with anticyclones. In the central latitudes, where one finds anticyclones, large-scale downward motions take place which appear to limit the height to which the smoke rises.

Smoke output estimates are given below. The stock of dry combustible material in the most productive forests of middle latitudes of the northern hemisphere is 25–30 kg/m². Approximately 15–20 per cent of this material is easily inflammable and can be burnt up completely -- moss, dead twigs and leaves. In pine woods the stock of needles is 0.6 kg/m²; in cedar woods it is 0.2–1.1 kg/m²; in broad-leaved forests the fallen dry matter is nearly 0.3 kg/m². The stock of dry combustible material in the timber of, for example, pine woods totals from 8 to 30 kg/m². In forests of low productivity, the stocks of dry material are not large -- just below 1 kg/m². The average stock of dry timber is about 15 kg/m².

Observations of forest fires suggest that twigs up to 4 cm in diameter burn out completely, and overall, 15–20 per cent of timber burns out. The fallen dead material burns out completely as a rule. The proportion of burnt-out peat varies greatly. Thus, excluding peat, the average figure for burnt-out material in forests is 5–10 kg/m². The smoke output for the burnt-out dry timber is approximately 2 per cent by mass. This result was derived from a special experiment on estimated smoke output according to LIDAR (light detecting and ranging) data from burning out a stock of timber. The stock, with the dimensions 6 x 6 x 2.5 m and a weight of 9 tonnes, gave 160 kg of smoke, which is 1.8 per cent of the initial weight.

Smoke estimates made by Golitsyn, based on Soviet data on forest fires, showed that the quantity of aerosol particles getting into the atmosphere from fires covering 1 million km² may total 150 million tonnes in summer, with lower estimates for the rest of the year. This amount of smoke can be instrumental in changing the regular structure of atmospheric temperatures and cause significant cooling of the land masses.

In addition to forest fires, the phenomenon of nuclear winter can be brought about by city, gas and oil fires. In major cities the quantity of combustible materials goes up to hundreds of kilograms per square metre. According to Ambio and successive publications, fires in inhabited areas produce at least double the amount of smoke and soot in the atmosphere compared to forest fires. One should further bear in mind that particles produced by burning oil products and plastics absorb solar radiation more intensely than those from forest fires.
From: "The Environmental Consequences of Nuclear War", report of the Steering
Committee for ICSU/SCOPE, September 1985.*

"All of the simulations indicate a strong potential for large-scale weather
disruptions as a result of extensive post-nuclear fires. These models, however,
still have important simplifications and uncertainties that may affect the fidelity
and details of their predictive performance, but probably not the general character
of the physical response. One potentially important exception is the inability of
present models to treat adequately mesoscale processes and microphysical evolution
of the smoke particles and the consequent effects on dispersion and scavenging of
smoke plumes. After careful analysis, we have arrived at the following main
conclusions:

For massive smoke injections at altitudes near or above several kilometers,
occurring during the growing season in the Northern Hemisphere, land surface
temperatures beneath dense, patchy, smoke clouds have been estimated to decrease
temperatures in mid-continental sites to 20-40°C below normal within a few days
(depending on the duration of the dense smoke and the meteorology of the particular
location). Some of these smoky patches may be carried long distances and create
episodic cooling. Weather anomalies could be spatially and temporarily quite
variable during this initial period if dense smoke situations that allow nearly no
sunlight through to the surface alternate with clearer conditions or thin smoke
situations during which a substantial fraction of sunlight could reach the surface.

Smoke would be spread throughout the Northern Hemisphere, in one to two weeks,
although the smoke layer would be far from homogeneous. For injections during the
growing season, solar heating of the particles could rapidly warm the air and lead
to net upward motion of a substantial fraction of the smoke to higher levels.
Here, particle lifetimes in the unperturbed atmosphere are generally months to
years. This warming of the upper troposphere would stabilize the atmosphere and
suppress vertical air movements, extending the lifetime of smoke in that region
from weeks to perhaps months.

Average summertime land surface temperatures in the Northern Hemisphere
mid-latitudes could drop to levels typical of fall or winter for periods of weeks
or more with convective precipitation being essentially eliminated. These cold air
layers might initially lead to fog and drizzle, especially in coastal and lowland
regions. In continental interiors, periods of very cold, mid-winter-like
temperatures are possible. In wintertime, light levels would be strongly reduced,
but the initial temperature and precipitation perturbations would be less
pronounced and might be essentially indistinguishable in many areas from an
anomalously cold winter. However, such conditions would occur simultaneously over
the entire mid-latitude region of the Northern Hemisphere and freezing cold air
outbreaks could penetrate southward into regions that rarely or never experience
frost conditions.

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* At the time of preparation of the present compilation, the full report
was not available to the Secretariat. This material is from the summary of the
report provided to the United Nations Secretariat by the Chairman of the Steering
Committee in response to the request in General Assembly resolution 39/148 F.
For large smoke injections, in Northern Hemisphere subtropical latitudes temperatures in any season could drop well below typical cool season conditions. Temperatures could be near or below freezing in regions where temperatures are not moderated by the warming influence from oceans. The convectively driven monsoon circulation, which is of critical importance to subtropical ecosystems and agriculture, and the main source of water, could be essentially eliminated. Smaller scale, coastal precipitation might, however, be initiated.

Strong solar heating of the smoke injected in the Northern Hemisphere between April and September would carry it upwards and equatorward, strongly augmenting the normal high altitude flow to the Southern Hemisphere (where the initial downward motion induced there could tend to suppress precipitation slightly). Within one or two weeks, thinned smoke layers may appear in the low to mid-latitude regions of the Southern Hemisphere as a precursor to a more uniform but still thin, veil of smoke that could soon follow and perhaps induce, modest cooling of land areas not well buffered by oceanic heating. Since in mid-latitudes it would already be the cool season, temperature reductions would not likely be more than several degrees. However, in more severe, but less probable, smoke injection scenarios, climatic effects in the Southern Hemisphere could be enhanced, significantly, particularly during the following spring and summer.

Much less analysis has been done on the recovery processes of the atmosphere from the several week acute climatic phase following the near global-scale spread of a substantial injection of the smoke that could occur from a Northern Hemisphere nuclear war during the growing seasons. Significant uncertainties remain concerning estimation of the potential removal rate of smoke particles by precipitation scavenging, chemical oxidation, and other physical-chemical factors. Dynamic transport and subsidence is also uncertain, both for particles in the sunlit and stabilized upper troposphere and stratosphere and in the winter polar regions, where attenuated sunlight and radiative, long-wave cooling could result in the circulation of particles out of the stratosphere.

Present estimates suggest that smoke lofted to 10 kilometres and above, either in fire plumes or under the influence of solar heating, could remain in the atmosphere for a year or more and induce long-term global-scale cooling of several degrees or more, especially after the oceans had cooled. For such conditions, precipitation could also be reduced significantly. Reduction of the summer monsoon intensity over Asia and Africa may be a particular concern.

..."
V. DUST AND SOOT


"It is common knowledge that the Sun's rays warm up the land and the oceans, which in turn heat up the atmosphere. It is also known that the Earth's atmosphere is much more transparent to solar radiation than to the thermal radiation emitted by water and land surfaces. As a result, the Earth's atmosphere is some 30°C warmer than it would be if the atmosphere were equally transparent to solar and thermal radiation. These 30° constitute the so-called 'greenhouse' effect of the Earth's atmosphere.

Filling the atmosphere with particles which scatter the solar radiation (dust) and absorb it (smoke) decreases sharply the amount of solar energy reaching the surface of the Earth. In addition the absorbing aerosol renders the atmosphere about as transparent to solar radiation as it is to thermal electromagnetic radiation. Thus, when it is saturated with aerosol, the greenhouse effect of the atmosphere is decreased.

The thermal effect of aerosol is, in certain respects, similar to the effect produced by clouds. As is known, clouds in daytime (or in summer) cool the land by reflecting part of the solar radiation, but at night (or in winter) they moderate temperature falls by constraining the thermal emission of the surface. Aerosol tempers fluctuations of temperature in time and space in the same manner, regulating fluxes of solar and thermal radiation in the atmosphere. The effect depends on optical properties and the height or location of an aerosol cloud. For instance, sulphuric aerosol and dust particles find their way into the Earth's stratosphere after major volcanic eruptions and, staying in it for a year or two, cause a decrease of the surface temperature.

Smoke, soot and especially such products of city fires can virtually bar energy from reaching the surface of the Earth. As a result, solar radiation is absorbed solely by the atmosphere. In this case, the surface is warmed by thermal emission of the atmosphere, not by solar radiation. The temperature of the surface drops by tens of degrees centigrade, coming close to the temperature of the aerosol layer which has absorbed the solar radiation. As a consequence, the greenhouse effect becomes disabled, leading to nuclear night and nuclear winter.

Smoke warmed by the Sun spreads upwards and sideways from the sources of the fire. In about one month, a huge cloud of smoke and dust may envelope the northern hemisphere and begin spreading into the southern hemisphere. Over the oceans the smoke cloud perceptibly raises the temperature of the lower layers of air. Smoky atmosphere over the oceans absorbs both solar radiation and heat emission of a cooling ocean, and thus has its temperature raised even more.

Such contrasting temperatures between ocean and land produce a situation well known to meteorologists: winter monsoon of the dry season in southern and south-east Asia. City and forest fires will proceed for about a week, and in one
month a dense cloud of microscopic particles of smoke and dust will cover both hemispheres. Land temperatures in the interior of the continents, even in the tropical belt, will go down to 0°C.

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"Particles in the atmosphere can affect the earth's radiation balance in several ways: by absorbing sunlight, by reflecting sunlight back into space and by absorbing or emitting infrared radiation. In general a cloud of fine particles -- an aerosol -- tends to warm the atmospheric layer it occupies, but it can either warm or cool the underlying layers and the surface, depending on whether the particles absorb infrared radiation more readily than they reflect and/or absorb visible light.

The anti-greenhouse effect of an aerosol is maximized for particles that are highly absorbing at visible wavelengths. Much less sunlight reaches the surface when an aerosol consists of dark particles such as soot, which strongly absorb visible light, than when an aerosol consists of bright particles such as soil dust, which mainly scatter the light. Consequently in evaluating the possible climatic effects of a nuclear war particular concern should be focused on the soot particles that are generated by fires, since soot is one of the few common particulate materials that absorb visible light much more strongly than they absorb infrared radiation.

How much an aerosol will cool the surface (by blocking sunlight) or warm the surface (by enhancing the greenhouse effect) depends on the size of the particles. If the average diameter of the particles is less than a typical infrared wavelength (about 10 micrometers), the infrared opacity of the aerosol will be less than its visible opacity. Accordingly an aerosol of very fine particles that even weakly absorb sunlight should have a visible effect greater than its infrared effect, giving rise to a significant cooling of the lower atmospheric layers and the surface. In the case of soot this is true even for somewhat larger particles.

The visible and infrared radiation effects associated with particle layers also depend on the thickness and density of the aerosol. The intensity of the sunlight reaching the ground decreases exponentially with the quantity of fine, absorbing particulate matter in the atmosphere. The infrared radiation reaching the ground, however, depends more on the air temperature than it does on the quantity of aerosol. Hence when a large amount of aerosol is present, the dominant climatic consequence tends to be strong surface cooling.

The "optical depth" of an aerosol (a measure of opacity equal to the negative natural logarithm of the attenuation of an incident light beam by absorption and scattering) serves as a convenient indicator of the aerosol's potential climatic
effects. For example, a cloud with an optical depth of much less than 1 would cause only minor perturbations, since most of the light would reach the surface, whereas a cloud with an optical depth of 1 or more would cause a major disturbance, since most of the light would be absorbed in the atmosphere and/or scattered away into space. Although volcanic particles happen to have an optimal size of enhancing visible effects over infrared effects, the magnitude of the induced surface cooling is limited by the modest optical depth of volcanic aerosols (less than about 0.3) and by their very weak intrinsic absorption at visible wavelengths. Nevertheless, the largest volcanic clouds may disturb the earth's radiation balance enough to cause anomalous weather. Much more significant climatic disturbances could result from the huge clouds of dust that would be thrown into the atmosphere by the impact of an asteroid or a comet with a diameter of several kilometers or more. These dust clouds could have a very large optical depth, perhaps initially as high as 1,000.

The radiative effects of an aerosol on the temperature of a planet depend not only on the aerosol's optical depth, its visible absorptivity and the average size of its particles but also on the variation of these properties with time. The longer a significant optical depth can be sustained, the closer the surface temperature and the atmospheric temperature will move toward a new state of equilibrium. Normally it takes the surface of the ocean several years to respond to changes in the global radiation balance, because of the great heat capacity of the mixed uppermost layer of the ocean, which extends to a depth of about 100 meters. In contrast, the air temperature and the continental land temperature approach new equilibrium values in only a few months. In fact, when the atmosphere is strongly cooled, convection above the surface ceases and the ground temperature falls rapidly by radiative cooling, reaching equilibrium in a few days or weeks. This happens naturally every night, although equilibrium is not reached in such a short period.

Particles are removed from the atmosphere by several processes: falling under the influence of gravity, sticking to the ground and other surfaces and scavenging by water clouds, rain and snow. The lifetime of particles against "wet" removal depends on the frequency of cloud formation and precipitation at various altitudes. In the first few kilometers of altitude in the normal atmosphere particles may in some places be washed out in a matter of days. In the upper troposphere (above five kilometers) the average lifetime of the particles increases to several weeks or more. Still higher, in the stratosphere (above 12 kilometers), water clouds rarely form and so the lifetime of small particles is typically a year or more. Stratospheric removal is primarily by gravitational settling and the large-scale convective transport of the particles. The deposition of particles on surfaces is very inefficient for average-size smoke and dust particles, requiring several months for significant depletion.

Clearly the height at which particles are injected into the atmosphere affects their residence time. In general, the higher the initial altitude, the longer the residence time in the normal atmosphere. Massive injections of soot and dust, however, may profoundly alter both the structure of the atmosphere and the rate of particle removal.
Nuclear explosions at or near ground level throw up huge amounts of dust. The principal dust-forming mechanisms include the ejection and disaggregation of soil particles from the crater formed by the explosion; the vaporization and subsequent renucleation of soil and rock, and the lifting of surface dust and smoke. A one-megaton explosion on land can excavate a crater hundreds of meters in diameter, eject several million tons of debris, lift between 100,000 and 600,000 tons of soil to a high altitude and inject between 10,000 and 30,000 tons of submicrometer dust particles into the stratosphere. The height at which the dust is injected depends on the yield of the explosion: the dust clouds produced by explosions with a yield of less than about 100 kilotons will generally not penetrate into the stratosphere, whereas those from explosions with a yield of more than about a megaton will stabilize mainly within the stratosphere. Explosions above the ground can also raise large quantities of dust, which is vacuumed off the surface by the rising fireball. The combined effects of multiple explosions could enhance the total amount of dust raised to high altitudes.

The quantity of dust produced in a nuclear war would depend sensitively on the way the weapons were used. Ground burst would be directed at hard targets, such as missile silos and underground command posts. Soft targets could be attacked by air bursts as well as ground bursts. There are more than 1,000 missile silos in the continental U.S. alone, and at least two Russian warheads are probably committed to each of them. Some 1,400 missile silos in the U.S.S.R. are similarly targeted by U.S. warheads. Air bases and secondary airfields, submarine pens and command and control facilities are among the many other strategic targets to which ground bursts might be assigned. In short, it seems quite possible that at least 4,000 megatons of high-yield weapons might be detonated at or near ground level even in a war in which cities were not targeted, and that roughly 120 million tons of submicrometer soil particles could be injected into the stratosphere in the North Temperate Zone. This is many times greater than all the submicrometer dust lifted into the stratosphere by the eruption of the volcano El Chichón in Mexico in 1982 and is comparable to the global submicrometer dust injections of much larger volcanic eruptions such as that of Tambora in 1815 and Krakatoa in 1883.

Analogies between the atmospheric effects of a major volcanic explosion and a nuclear war are often made for convenience. Nevertheless, there is no straightforward way to scale the effects of a volcanic explosion against those of a series of nuclear detonations. The aerosol particles produced by volcanoes are fundamentally different in composition, size and shape from those produced by nuclear explosions. We have therefore based our calculations on the properties of dust measured directly in nuclear-explosion clouds.

The only proper comparison between a volcanic eruption and a nuclear explosion is the optical depth of the long-term aerosols that are produced. In fact, we utilized data on global "dust veils" generated by volcanic explosions to test and calibrate our climate models. In so doing we have been able to account quantitatively for the hemispheric surface-cooling effect observed after major volcanic eruptions. The present nuclear-dust calculations are entirely consistent with observations of volcanic phenomena. For example, it is now clear that violent eruptions can lead to a significant climatic cooling for a year or more. Even so, in recorded history volcanoes have had only a rather modest climatic role. The fact that volcanoes are localized sources of dust limits their geographic

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influence; moreover, volcanoes inject comparatively little fine dust (and no soot) into the stratosphere. Nuclear explosions, on the other hand, are a powerful and efficient means of injecting large quantities of fine soot and dust into the atmosphere over large regions.

The atoms produced in the fission reactions of a nuclear explosion are often in unstable isotopic states. Radioactive decay from these states releases alpha, beta and gamma radiation. In most nuclear weapons at least half of the energy yield is generated by fission and the rest by fusion. About 300 distinct radioactive isotopes are produced. Most of them condense onto aerosols and dust formed in (or sucked into) the fireball. Accordingly the dust and the radioactivity generated by nuclear explosions are intimately related.

Of particular interest here are the prompt and the intermediate radioactive fallout. The former is associated with short-lived radioactive isotopes that condense onto large soil particles, which in turn fall to the ground within hours after an explosion. Intermediate fallout is associated with longer-lived radioactive isotopes carried by smaller particles that drift in the wind and are removed by settling and precipitation in the interval from days to months. Prompt fallout is generated by ground bursts, and intermediate fallout is generated by ground bursts and air bursts in the yield range from 10 to 500 kilotons, which deposit their radioactivity in the middle and upper troposphere.

The danger from radioactive fallout is measured in terms of the total dose in rads (a unit of radiation exposure equivalent to 100 ergs of ionizing energy deposited in one gram of tissue), the dose rate in rads per hour and the type of radiation. The most deadly effects are caused by the intense, penetrating gamma radiation from prompt fallout. The widespread intermediate fallout delivers a less potent long-term gamma-ray dose. A whole-body gamma-ray exposure of 450 rads, received over several days, is lethal to half of the healthy adults exposed. Chronic doses of 100 rads or more from intermediate fallout could suppress the immune system even of healthy people and would cause long-term increments in the incidence of cancer, genetic defects and other diseases.

Our most recent studies of the effects of radioactive fallout in our baseline case indicate that the prompt fallout could contaminate millions of square kilometers of land with lethal radioactivity. The intermediate fallout would blanket at least the North Temperate Zone, producing average long-term, whole-body gamma-ray exposures of about 50 rads in unprotected populations. Internal exposures of specific organs to biologically active radioactive isotopes such as strontium 90 and iodine 131, which enter the food chain, could double or triple the total doses. According to Joseph B. Knox of the Lawrence Livermore National Laboratory, if nuclear power plants were targeted directly, the average long-term gamma-ray dose could be increased to several hundred rads or more.

... How a smoke cloud extinguishes light also differs from how a dust cloud does so. A sooty pall of smoke absorbs most of the incident light and scatters only a small fraction back into space or down toward the surface. The absorption rapidly heats the smoke clouds, inducing powerful air motions and winds. Dust clouds, on the other hand, primarily scatter the incident sunlight and absorb only a small
fraction. To block light effectively clouds that are purely light-scattering must be very thick, because much of the light is scattered forward toward the earth’s surface; for example, ordinary water clouds typically have an optical depth of 10 or more.

We find that for many scenarios a substantial reduction in sunlight may persist for weeks or months after the war. In the first week or two the clouds would also be patchy; hence our calculations probably underestimate the average light intensity at these early stages. Nevertheless, within the target zones it would be too dark to see, even at noon.

The large amount of smoke generated by a nuclear exchange could lead to dramatic decreases in continental temperatures for a substantial period. In many of the scenarios represented in the illustrations accompanying this article land temperatures remain below freezing for months. Average temperature decreases of only a few degrees Celsius in spring or early summer could destroy crops throughout the North Temperate Zone. Temperature drops of some 40 degrees C. (to an absolute temperature of about -25 degrees C.) are predicted for the base-line case, and still severer cooling effects are possible with the current nuclear arsenals and with those projected for the near future.

The predicted changes in air temperature as a function of height and time for our 5,000-megaton base-line scenario reveal several important features. First, the upper atmosphere is heated by between 30 and 80 degrees C. as the sunlight, which normally warms the ground, is absorbed in the highest smoke layers. At the same time the ground cools in darkness. The hot clouds, like hot-air balloons, would not remain stationary but would rise and expand.

A month after a massive nuclear exchange the entire troposphere over land could be thermally brought to a stand-still. Even after three months only the lowest few kilometers would receive enough solar energy to drive weak convection. In effect the stratosphere would descend to the surface, creating an alien atmosphere. In some places warm currents of ocean air would still sweep into the continents at ground level, but this heat source would be able to drive convection only within the lowest few kilometers of the atmosphere. The intense temperature inversion would effectively damp deep convective activity. Elsewhere cold air flowing off the continents might warm over the oceans, rise and recirculate over the continents and finally subside over the land.

One possible consequence of the temperature inversion caused by such a smoke cloud would be an increase in the atmosphere residence time of the smoke and dust. This outcome represents a positive feedback effect, not taken into account in any calculations so far, that would increase both the severity and the duration of the nuclear winter. The temperature inversion reduces the convective penetration of moist air from below, inhibiting the condensation of water in the sooty air and hence greatly limiting precipitation at altitudes higher than a few kilometers. The longer soot and dust remain in the atmosphere, the farther they spread horizontally and the more widespread their climatic impact is. Under these conditions the particles are removed mainly by continuing coagulation and fallout and by transport in global-scale wind systems and turbulence to low altitudes where precipitation scavenging still takes place.

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Our calculated temperature changes over extended land masses do not account for the initial patchiness in the clouds or the later dilution of cold continental air by warm marine air. Michael C. MacCracken of Livermore has investigated the combined effects of patchiness in clouds and the transfer of heat from the ocean, working with a general-circulation model to trace large blobs of smoke; he has also worked with a two-dimensional climate model to calculate land temperatures corresponding to the smoke emission in our 5,000-megaton base-line scenario. He finds average temperature decreases on land that are roughly half our continental-interior temperature drops. Even more sophisticated three-dimensional general-circulation-model calculations for conditions similar to our base-line scenario confirm that temperature drops of between 20 and 40 degrees C. are possible over vast continental areas.

The results of our computations indicate that the motions induced in soot clouds by the absorption of sunlight might cause the soot cloud to rise and spread out horizontally. This phenomenon could accelerate both the early dispersal and the global spreading of smoke plumes, a process that is otherwise dominated by wind shear and turbulence. Recently a group at the National Aeronautics and Space Administration's Ames Research Center, consisting of Robert M. Haberle and two of us (Ackerman and Toon), applied an advanced two-dimensional global-circulation model to compute the motion of heated soot clouds in the earth's troposphere. The Ames group considered a uniform soot cloud between 30 and 60 degrees north latitude, encircling the earth at these latitudes and extending from the ground to an altitude of eight kilometers. This smoke simulation shows massive fragments of the cloud rising high into the stratosphere and moving briskly toward the Equator and the Southern Hemisphere.

Although these calculations are preliminary, they support a major hypothesis of our initial study: that self-propelled smoke and dust clouds from the Northern Hemisphere could be rapidly transported to the Southern Hemisphere, causing large climatic anomalies there as well. Such accelerated dispersal could have the most severe consequences in the Tropics of both hemispheres, where the indigenous organisms are extremely sensitive to dark and cold. A nuclear winter extending to the Tropics would represent an ecological disaster unprecedented in history.

Our speculations about major meteorological disturbances and interhemispheric transport following a nuclear conflict have received further support from sophisticated calculations with three-dimensional models of global circulation. These models are not yet detailed radiative-transport calculations. Nevertheless, they are able to define the initial three-dimensional perturbations in winds and temperatures caused by massive smoke injections. Two research groups have made these advanced climate studies: Curt Covey, Stephen H. Schneider and Starley L. Thompson of the National Center for Atmospheric Research (NCAR) in Boulder, Colo., and Vladimir V. Alexandrov and Georgi L. Stenchikov of the Computing Center of the Academy of Sciences of the U.S.S.R.

The predictions made by both groups of the normal and perturbed meridional, or north-south, circulation of the atmosphere several weeks after a nuclear exchange in the Northern Hemisphere in the spring or summer lead to the same conclusion: the normally bifurcated "Hadley cell" circulation in the Tropics would be transformed into a single intense cell with strong winds in the upper troposphere

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flowing directly from the Northern Hemisphere to the Southern Hemisphere. This would represent a profound change in the global wind system.

The average meridional circulation is the residual motion of large-scale planetary-wave oscillations. The global-circulation models predict anomalies in the planetary-wave motions, and here too the results are surprising. The NCAR group finds that continent-size bodies of heated air could penetrate deep into the Southern Hemisphere in a matter of days. Essentially all the habitable land masses of the earth could be subject to rapid blackout by soot. The global-circulation models also forecast subfreezing temperatures over most of the northern continental regions. What is startling is that local freezing could occur within two or three days; the NCAR group refers to it as a "quick freeze". Under such circumstances practically no area of the globe, north or south, would be safe from nuclear winter.

Consideration of the possible weather activity near coastlines during the nuclear winter suggests that even if the incident sunlight were reduced significantly, the oceans would continue to feed heat and moisture into the marine boundary layer near coastlines. In some regions cold offshore winds would interact with the marine environment to produce intense storms and heavy precipitation. In other regions, as prevailing winds swept ocean air onto cold continents, thick stratus clouds and continuous precipitation could ensue. It is not known how far this severe weather might extend inland from the coastlines, but a 100-kilometer margin would probably include most of the activity.

... Our study also considered a number of secondary climatic effects of nuclear war. Changes in the albedo, or reflectivity, of the earth's surface can be caused by widespread fires, by the deposition of soot on snow and ice and by regional modifications of vegetation. Short-term changes in albedo were evaluated and found to be unimportant compared with the screening of sunlight. If significant semipermanent albedo changes were to occur, long-term climatic shifts could ensue. On the other hand, the vast oceanic heat source would act to force the climate toward contemporary norms following any major disturbance. Accordingly we have tentatively concluded that a nuclear war is not likely to be followed by an ice age.

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"Our results qualitatively agree with the fundamental conclusion of the lower-dimensional models, that is, for plausible scenarios. Smoke generated by a nuclear war would lead to dramatic reductions in land surface temperature. Furthermore, the three-dimensional results suggest the possibility of rapid freezing of land surfaces under transient patches of smoke that may be randomly transported by atmospheric winds. We also find significant changes in atmospheric circulation which in many cases would probably spread the smoke far beyond the altitude and latitude zones in which it was initially injected.

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Clearly, further study of current model results and a greater variety of smoke injection scenarios are necessary both to analyse thoroughly physical mechanisms and to examine additional important climatic variables. Also, it should be clear that the problem is intrinsically a dynamic one. Within a few days atmospheric winds and temperature would be so profoundly altered that any estimates of aerosol spreading or removal based on today's conditions become highly questionable.

More modest improvements in model simulation should include more realistic specification of the radiative effects of aerosols, that is, inclusion of IR absorption and emission and scattering of sunlight by the aerosols. One-dimensional sensitivity studies indicate that inclusion of IR cooling due to smoke of visible optical depths less than -10 would lead to only a small reduction in the amount of mid-atmospheric warming, and that the surface greenhouse warming would be quite small. The same studies imply that inclusion of scattering by the smoke aerosols would slightly decrease the amount of surface cooling because the aerosols will scatter some sunlight down to the surface. However, dust raised by the nuclear explosions, also not included in this study, will enhance surface cooling by backscattering sunlight to space, removing energy from the Earth-atmosphere system. Moreover, such stratospheric dust or smoke scattering would also reduce the upper tropospheric heating rate for the purely absorbing smoke case, changing the calculated atmospheric circulation.

Physical processes incorporated into GCMs - including assumptions of fixed sea temperatures and zero land surface heat capacity, crude near-surface atmospheric representation, and sub-grid scale parameterizations for vertical and horizontal heat transport and for cloud properties - must also be critically examined. For example, vertical transport of heat by sub-grid scale processes would be affected by the dramatic increase in atmospheric stability obtained in our study. Nevertheless, our basic results for a 2 x 10^14 g stabilized smoke cloud - strong land surface cooling, mid-atmospheric warming, and profound changes in circulation - seem robust; they are confirmed both by the lower-dimensional models discussed above and by results from a simplified GCM with different sub-grid scale parameterizations and with more realistic (finite) surface heat capacity. But important details such as the initial patchy freezing are highly tentative, dependent on both the model and the initial conditions.

We believe the largest uncertainties in the nuclear aerosol/climate problem lie in translating the estimated inventory of burnable fuels in cities and forests into stabilized smoke clouds on a spatial scale suitable for global atmospheric circulation models. The way fires will burn (for example, wildfires), the height to which smoke is injected, the duration of fires, the particle concentration within the initial smoke plumes, and early particle removal by rainout in convective/mesoscale circulations all occur on spatial scales smaller than the resolution of any general circulation model now available. Unless the current estimates of the effect of these processes are substantially in error, however, strong cooling of mid-continental land surfaces below regional-scale smoke clouds is very plausible. Moreover, patchy, transient subfreezing outbreaks could be plausible even if hemispheric scale stabilized smoke clouds were many times smaller than the 2 x 10^14 g we assumed.
Thus, the problem of long-term consequences of nuclear war represents not only an obviously critical issue for mankind, but also a stringent test of current understanding of the causes of climatic change. By subjecting models to the massive perturbation of several optical depths of aerosol, we gain insights into both model behaviour and properties of the real atmosphere which would not necessarily be as evident from studies of much smaller perturbations. Thus, we may draw implications for scientifically related problems such as the effects of volcanic eruptions on the climate and the possible massive dust injection resulting from the postulated impact of an asteroid on the earth at the end of the Cretaceous period. It is our hope that a full hierarchy of models will be brought to bear on the question of nuclear war atmospheric effects.

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"The other source of atmospheric particulate material is from soil dust that is vaporised and recondensed or merely raised during the explosion. The NAS (1975) report suggests that $10^3$ to $10^4$ tons ($10^6$ to $10^7$ kg) of submicron material are produced per 1000 kiloton nuclear yield. This is consistent with Izraïl and Ter-Saakov's (1974) estimate of 200 tons of fused soil in the fireball per kiloton yield given that this latter estimate represents all sizes of particles. This NAS (1975) estimate of submicron particles produced by the explosion represents about $10^{-4}$ of the soil removed from the crater by a surface burst of a nuclear weapon.

Some sources of aerosol from fires will persist after the initial nuclear exchange. When nuclear weapons are exploded as airburst near forests then outside the zone incinerated in the initial fire following the explosion there will be a further zone where 30 per cent of the trees are uprooted and the remainder have branches and leaves blown from them (Glasstone and Dolan 1977). This devastated forest material will dry out and burn when meteorological conditions are favourable and ignition occurs.

Also there will be other areas outside the incinerated zone affected by surface bursts. This can happen where the early fallout occurs over a forest area and the radiation dose exceeds the dose required to kill the trees. The total radiation dose levels required to kill trees are more than or equal to 1800 roentgens for coniferous trees and more than or equal to 5000 roentgens for deciduous trees (Woodwell 1982). No information is available on the dose required to kill trees in tropical forests so we assume it is more than or equal to 5000 roentgens. When these levels are exceeded due to early fallout, most of the cumulative dose is received in a day or two of the explosion and the tree canopy will rapidly die. No doubt these forest areas also will burn as soon as conditions are favourable for combustion. We have calculated the areas affected in this way from fallout patterns (Glasstone 1962) with weighting according to the proportion of forests on each continent that are coniferous and non-coniferous (due to the
typically receive around 1 Mt of nuclear explosive. We estimate that the total area of cloud initially produced (neglecting overlap) would be in the Southern Hemisphere 0.2 to 2 per cent of the hemispheric area and in the Northern Hemisphere 7 to 40 per cent of the hemispheric area. In the Southern Hemisphere the question of overlap is not important because even the most extensive cover of the clouds (less than or equal to 2 per cent) is a very small fraction of the hemispheric area. However, in the Northern Hemisphere the area of potential smoke and dust aerosol cloud cover (7 to 40 per cent) is sufficiently large to obscure much of the sky and so the question of overlap reducing the cloud extent is important. ... 75 per cent of the total nuclear explosive yield will be used in China, Europe, USA and USSR whose combined land area is 18 per cent of the Northern Hemisphere. Alternatively we note that in the Ambio Scenario I, around 91 per cent of the total nuclear weapons yield is exploded between 20°N and 60°N (H. Rodhe unpublished data). Inspection of the Ambio Scenario Targets are dispersed over the area covered by the USA, Europe, USSR west of the Aral Sea, eastern China, North and South Korea and Japan. This area, about one half of the land area between 20°N and 60°N or 12 per cent of the hemispheric area, represents a reasonable upper limit to the initial dispersion of the smoke and dust clouds during the 24 hrs following the commencement of the war, rather than the 18 per cent or 40 per cent discussed above. We estimate the aerosol loading of these clouds ... to be 0.2 to 2 g m⁻² in the Southern Hemisphere and 6-13 g m⁻² in the Northern Hemisphere. The higher loadings in the Northern Hemisphere result from both the greater proportion of urban and forest targets in that hemisphere and the considerable overlap of plumes in that hemisphere.

The aerosol produced during and subsequent to a nuclear war will undergo transformations in the atmosphere. Here we are primarily concerned with the attenuation of sunlight (direct plus scattered) reaching the earth's surface. The attenuation of sunlight by aerosol is dependent on the refractive index of the aerosol, which determines the proportion of scattering versus absorption, on the geometric cross sections of the particles involved and on an optical extinction coefficient dependent on refractive index, particle radius and wave length (Friedlander 1977, Twomey 1977).

The attenuation of sunlight is calculated using the parameterised scheme for radiation scattering and absorption in aerosol layers developed for thick clouds on Venus (Sagan and Pollack 1967). Beneath the aerosol clouds which cover more than or equal to 2 per cent of the Southern Hemisphere the intensity of sunlight at noon is estimated to be at most approximately 20 per cent of that on a normal day.

These clouds in the Southern Hemisphere will probably have no large environmental impact. They will be carried by winds around the hemisphere and dispersed in a few days. The total aerosol mass predicted for injection in the Southern Hemisphere lies somewhere between the mass injected by the Krakatoa (1883) and Agung (1963) volcanoes (Deirmendjian 1973). The climatic impact of these volcanoes, and by analogy the dust from nuclear weapons in the Southern Hemisphere, while detectable (NAS 1975) would be insignificant compared with the more direct effects of these explosions.
different lethal radiation doses of coniferous and non-coniferous forests). These forests are presumed to burn when meteorological conditions are conducive and accidental or deliberate ignition takes place during the six months (covering summer, autumn and early winter in the Northern Hemisphere) following the Ambio scenario war which occurs on June 10.

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Around half the aerosol emission comes from city fires and the other half is made up of approximately equal contributions from dust rise, forest fires and the burning of fuel storages. The only quantifiable source of postwar aerosol emission is that due to delayed forest burning in zones killed by radioactivity. These areas are 0.5 to 1.5 \times 10^4 \text{ km}^2 in the Southern Hemisphere and 2 to 6 \times 10^5 \text{ km}^2 in the Northern Hemisphere.

The total aerosol production during the initial exchange is approximately 10 \times 10^{12} \text{g} in the Southern Hemisphere and 200 \times 10^{12} \text{g} in the Northern Hemisphere.

We acknowledge that these estimates are uncertain, but insufficient information is available to assess the uncertainty. If none of the forest material burnt (an unlikely situation) the particulate production would be reduced by only 15 per cent. Alternatively it appears quite feasible, in the light of the figures we have examined, that the total aerosol emission could be much larger than the 'best estimate' arrived at here.

The initial distribution of this aerosol in the atmosphere may be estimated from information about the sources. The aerosol from fires will rise in the atmosphere.

We calculate this rise using conventional plume rise theory and the heat flux from the fuel combusted in the fire. This plume rise theory has been developed for a nuclear war fire scenario (Manins 1983). Typically we find for 1 Mt of total explosion on a particular target and assumed burning times of 1 hr for grassland and 3 to 24 hrs for forest and cities, the top of the plume reaches 7 km for grassland and 7 to 12 km for forests and cities. The centre line of these plumes would be at approximately 0.8 of the top height and the bottom of the plume would be at 0.6 of the top height i.e. the minimum height of these plumes will be around 4 km. The soil dust (submicron) will be distributed according to the final heights of the initial nuclear 'mushroom' clouds, and for Ambio Scenario I 90 per cent of the soil dust will be between 7 and 13 km. Thus the final aerosol layer will reside mainly between 4 and 13 km.

The horizontal extent of this initial aerosol layer is determined by the initial width of the plumes at their equilibrium height, the prevailing wind speed during the plume rise and the spacing between the targets (or the degree of overlap of the plumes). We assume that the plume from a fire from a 1 Mt target is typically 15 km wide at its equilibrium altitude and initially experiences a wind speed of 25 m s\(^{-1}\) at altitude (Palmen and Newton 1969). Thus the cloud size from a grass fire might be 1 \times 10^9 \text{m}^2. The Ambio Scenario has around 200 targets in the Southern Hemisphere and perhaps 5500 in the Northern Hemisphere, and these

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In the Northern Hemisphere the situation is more complex. The total aerosol 
mass injected from this hypothetical nuclear war is perhaps 10 times that injected 
by the Krakatoa volcano and more than 100 times the natural loading of the 
atmosphere (Twomey 1977). We calculate that the huge black clouds formed over the 
target areas with columnar aerosol loadings of 6-13 g m⁻² absorb 92 per cent and 
reflect 8 per cent of the incoming solar radiation, and transmit virtually no 
sunlight to the surface. There would be immediate effects on surface temperatures 
in continental areas away from oceans due to this blocking of sunlight. The 
darkness and cold (in inland regions) combined with the general shortage of medical 
facilities, food and shelter, will make the task of surviving more difficult for 
the remaining population.

The clouds have such large optical thickness, \( T = 50 \) to 100, that on average 
(assuming they were well mixed) all the absorption of solar radiation would take 
place in the top 1 km. This 1 km layer would experience an initial heating rate 
due to solar radiation of approximately 100 K day⁻¹ as a 24 hr average. The 
equilibrium temperature for this 1 km layer with this albedo would be at least 
270 K. The heating of the layer could cause the rapid buoyant convection of these 
clouds into the stratosphere. Once in the stratosphere, the lifetime of the clouds 
would be greatly prolonged permitting them to become dispersed over the whole globe 
and persisting for months to years. If 50 per cent of the aerosol emitted in the 
Northern Hemisphere by this hypothetical war was dispersed over the globe as an 
aerosol layer, its column mass loading would be 0.2 g m⁻², its optical depth 
would be approximately 1.5 and it would absorb or reflect approximately 80 per cent 
of the incoming solar radiation. As the circulation between the hemispheres is 
quite rapid above 20 km the Southern Hemisphere would not escape from such a global 
darkening event.

There are other processes which could affect the fate and the attenuation of 
sunlight by this aerosol layer. If these processes are rapidly effective they may 
modify the effects of the aerosol just described.

Processes affecting the optical depth of such clouds are:

1. the production of new aerosol particles,
2. the coagulation of aerosol particles,
3. the diffusion and dispersion of the aerosol throughout the atmosphere, and
4. the removal of this aerosol by precipitation scavenging and dry 
   deposition.

It should be stressed that these processes are interactive and that a proper 
evaluation of the subsequent fate of these aerosol clouds requires complex 
modelling not yet undertaken. Any change in the albedo or heating rate of the 
atmosphere will induce some change in atmospheric dynamics, cloud formation and 
precipitation. Obviously reduced precipitation through the aerosol clouds would 
increase their lifetime, whereas increased precipitation will reduce it. Changes 
in one direction or the other would be likely if such aerosol clouds entered the 
atmosphere. We believe that even the direction of such changes is presently 
unknown. In the absence of the modelling necessary to qualify these processes we
attempt to critically assess the time scales of processes 2, 3 and 4 in an unperturbed atmosphere and their likely effect on the attenuation of sunlight by the clouds.

The processes of coagulation and dispersion of aerosol are coupled because the coagulation rate is dependent on the square of the aerosol concentration. So dispersion of aerosol into clear air reduces the total coagulation rate. Furthermore, for a constant volume (or mass) of aerosol the optimum size aerosol for optical extinction is 0.25 μm radius (see Friedlander 1977, p. 135). The predominant size particles in fresh smoke is 0.05 μm radius. It takes 125 particles of 0.05 μm radius to make up the volume of one 0.25 μm radius particle, so substantial particle number reductions can occur while the optical depth of the smoke may even increase! We have previously calculated that the fresh smoke clouds have mass loadings of 6 to 13 g m⁻² distributed over 9 km depth. This corresponds with particle densities of 2 to 5 x 10⁴ particles/cm³ with a peak number density of 0.05 μm radius (Vines et al. 1971, Barton and Paltridge private communication).

Simple coagulation theory (Friedlander 1977, Twomey 1977) indicates that at these initial concentrations approximately 3 days are required for a factor of 10 decrease. We cannot assess the exact influence on optical depth of this particle number decrease as it requires complex coagulation calculations but considering the discussion above it is not obvious that the optical depth would greatly decrease during the first week or so of coagulation (e.g. see the aerosol distributions in Burgmeier, Blifford and Gillette 1973). Furthermore the abovementioned coagulation times would be lengthened by dispersion of this aerosol into the stratosphere or through the troposphere.

Simultaneously with this coagulation, there will be dispersion of these aerosol clouds throughout the atmosphere. The rate of dispersion in the troposphere depends on the initial size of the clouds and these differ greatly between the hemispheres. Reasonable estimates of the time for spreading of these aerosol clouds throughout the troposphere (if they do not pass into the stratosphere) are about one month for the Southern Hemisphere and two weeks for the Northern Hemisphere.

From studies of radioactive material (Lambert, Sanak and Polian 1983), of soot particles (Ogren and Charlson 1983) and of the frequency of occurrence of clouds and precipitation (Rodhe and Isaksen 1980) we estimate the average lifetime of submicron aerosol particles in the upper troposphere to be in the range 10 to 30 days and perhaps 10 times as long in the lower stratosphere (NAS 1975). This implies that the mass of such aerosol particles produced during and immediately following the war and contained in the upper troposphere would decline due to scavenging (by precipitation) to 30 per cent within two weeks to a month. The mass of aerosol particles in the lower stratosphere would decline similarly due to stratospheric-tropospheric exchange within three to twelve months.

The steady state loading of aerosol mass in the troposphere due to forest fires, and oil and gas well fires in the months after a nuclear war would be approximately 0.001 g m⁻² in the Southern Hemisphere and approximately 0.03 g m⁻² in the Northern Hemisphere. This loading is below the natural level in the Southern Hemisphere, but somewhere between the background level and that from the Krakatoa injection in the Northern Hemisphere and as such could cause marginally detectable climatic changes.
In summary it appears that fire-smoke and dust rise will form black clouds over all target areas following a nuclear war. Initially these clouds would only affect surface temperature in the Northern Hemisphere. However it is probable that some fraction of these clouds will buoyantly rise into the stratosphere and darken the sky globally for months. Alternatively if they remain in the troposphere (and they do not perturb the dynamics of the atmosphere and the frequency of precipitation) the clouds could coagulate, disperse and be scavenged during a few weeks after the war. In the latter case, the effects of the clouds on surface temperature and the weather would be confined to the Northern Hemisphere (provided there is no change in tropospheric interhemispheric exchange). The temperature and weather changes would last perhaps no longer than the clouds themselves.

It must be recognised that there is great uncertainty in many of the figures presented. Here we have attempted to take the most reasonable or median value for any particular term. In some cases the upper and lower limits are an order of magnitude different from the values chosen. The uncertainty in our final calculations is probably at least this large.

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"It is also quite possible that fallout of the large amounts of dark aerosol will lead to a substantial reduction in photosynthesis in the upper layers of the oceans and lakes. Under normal conditions, filter-feeding zooplankton very actively remove small-sized mineral and organic particles in a matter of weeks from the euphotic layer to the deep sea through their excretions (Delany, 1967; Alldredge and Madin, 1982; Degens and Ittekott, 1983; Deuser et al., 1983a, b). After the darkness period following a nuclear war, this biological cleansing mechanism may be much disturbed, so that oceanic productivity may remain reduced over considerable time, even after the clearing of the atmosphere. Another negative factor contributing to this may be that fire produced aerosols contain large amounts of harmful pollutants, e.g. trace metals (Hardy and Crecelius, 1981) and radioactive material.

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"Unlike soot from the long-lasting fires, dust from a nuclear explosion would be lofted to its stabilization altitude within 3 or 4 min, and, once a nuclear attack stopped, there would be no additional sources. Dust has an appreciable effect on climate only if it is of small size (submicron, or less than
one micrometer (1 μm) in radius) and if it is lofted to the stratosphere, where residence times are appreciable. (An altered state of the atmosphere would make estimates of residence times less certain. Consideration of dust lofted to all altitudes is required in climate simulations.) Lifting into the stratosphere requires a substantial explosion energy, a yield above roughly 1 Mt. Most of the following discussion will be based on idealized calculations for 1-Mt surface bursts (Zinn, 1973; Horak et al., 1982; Horak and Kodis, 1983).

... If a nuclear fireball is to raise significant amounts of dust to great altitudes, the burst must occur very close to the ground. One measure of the ability of a fireball to raise particles is the amount of fallout observed near the explosion. This local fallout consists mostly of the largest particles, those that cannot be long supported by the flow and that fall to the ground early in the cloud rise.

... For bursts in the air, those very close to the ground ("surface bursts") are most effective in raising dust. If the weapon were slightly buried, the total mass in the cloud would increase dramatically, but because much of the explosion energy is deposited in the ground and there is no radiative fireball, the cloud rise would be very modest. A surface burst can be loosely defined as one close enough to the ground that the primary interaction with the soil occurs through the agency of radiative transport instead of blast. The details will depend on the radiative characteristics of the specific weapon, but from Zinn’s (1973) hypothetical 1-Mt case it can be estimated that the burst height would have to be less than a few tens of meters.

X-rays would be deposited in a thin layer of rock or soil and would generate an intense shock wave in the ground. Close to ground zero, rock would be vaporized by the shock; farther out, rock would be melted; and finally, at greater distances, the rock would be displaced, creating a cloud of ejecta from the forming crater. All these processes would contribute to the dust load of the fireball. There are three additional sources of dust: the metal vapors that are the physical remains of the weapon, soil lofted in the so-called "thermal layer", and dust swept into the stem and fireball by afterwinds. These three mechanisms are not expected to be major sources of dust for surface bursts.

Recondensed vaporized material is an important source of fine particles in nuclear clouds from surface bursts. Most of the vapor is derived from rock and soil. Only a modest amount of metal is contained in a ballistic missile warhead.

The relative importance of the mechanisms that produce vapor from rock and soil varies with height of burst. If the bomb were exploded at or slightly below the surface, about half or more of the energy would be delivered as a strong shock propagated into the ground. Initially, this shock would be strong enough to vaporize rock. From calculations by Butkovitch (1974) for underground explosions, the amount of vaporized rock produced by a surface burst may be estimated at 0.04 Tg/Mt for a dense rock target (density of 2.6 g/cm³) and approximately...
0.06 Tg/Mt for a porous dry soil or a very porous dry rock target (density of 1.4 g/cm³).

In addition to vapor, a much larger mass of melted rock would be produced by the shock. For a surface burst on a dense rock target, about 0.5 to 0.6 Tg/Mt of rock would be shock melted; up to twice as much melt would be produced from porous targets. About half of the melt would be sprayed as a conical sheet out of the expanding crater. Both sides of the sheet would then be exposed to radiation from the fireball. Because temperatures in the early fireball would exceed the vaporization temperatures typical of rock melts (0.4 eV, or about 5,000 K), part of the ejected melt sheet would be vaporized. In a 1-Mt explosion the temperature of the fireball would drop below typical vaporization temperatures for rock melts after about 5 s. Local fireball temperatures adjacent to the melt sheet would drop below vaporization temperatures sooner, owing to transfer of energy to rock vapor and to increased opacity near the melt sheet. The enthalpy required to vaporize silica melts is of the order of 500 calories per gram (cal/g), and, if all the energy of the fireball were transferred to the rock vapor, the entire melt sheet from a dense target would be vaporized (about 0.3 Tg/Mt). The temperature of the fireball would drop below the vaporization temperature of the melt sheet long before this could happen, however. The thin leading edge of the melt sheet, which would be exposed longest and to the highest energy radiation, probably would be entirely vaporized, but negligible vaporization would occur from the late, thick trailing part of the ejecta sheet. From rough considerations of the geometry and velocity structure of the ejecta sheet and the temperature history of the fireball, it is estimated that probably no more than about one-tenth of the melt sheet (0.03 to 0.06 Tg/Mt) would be vaporized by radiation from the fireball.

The total amount of vaporized rock (shock-vaporized plus vaporized melt) expected from a surface burst therefore is of the order of 0.07 to 0.12 Tg/Mt, depending on the porosity and compressibility of the surface material.

The melt would also be the source of another class of small particles after the fireball cooled below the vaporization temperature. Divergent flow and aerodynamic disruption would break up the ejected melt sheet into droplets. Some of these droplets would remain sufficiently large that they would soon fall out of the fireball, but microscopic droplets would also be formed.

... The principal remaining sources of dust are solid particles ejected from the crater or swept up by the afterwinds. The size distribution of solid particles ejected from a surface burst crater is dependent on the characteristics of the target. Even from a crater produced in massive strong rock, a small fraction of the ejecta consists of micron and submicron particles.

... Most fine particles ejected from surface burst craters collide with and stick to larger fragments. As an upper bound, probably no more than about 1 percent of the total mass consisting of particles smaller than 1 um is carried to stabilization altitude in the fireball from a surface burst on a strong rock target.

...
Ejecta from craters produced in fine particulate target material, such as fine alluvium, may be expected to yield somewhat more than 0.1 Tg/Mt of fine solids entrained in the fireball, provided that the target is dry. In ejecta from wet targets, on the other hand, the mass of fine solid particles that are separated and entrained in the fireball may be less than 0.1 Tg/Mt, regardless of whether the material is strong rock or unconsolidated particles.

As height of burst is increased, delivery of energy to the shock in the ground drops rapidly. The principal sources of dust become particles condensed from vapor and particles swept up from the surface. At sufficiently low height of burst, some surface material would be completely vaporized by radiation from the early fireball and later would condense to fine particles as the fireball cooled. At greater distances, only water and other relatively volatile constituents would be vaporized by optical photons from the fireball. The gas thus produced would loft solid particles and melt droplets into the fireball.

Finally, as the fireball rose, the afterwinds would scour the surface. This scouring could be an important source of dust if a dry, fine particulate soil were present at the target or if previous bursts had dried, crushed, and loosened the soil and raised precursor dust clouds.

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In conclusion, materials directly vaporized by the nuclear explosion as well as ejecta melt are the principal sources of the fine particles lofted by nuclear clouds. Because these processes are relatively insensitive to soil and rock type, data from high-yield explosions on coral islands can reasonably be used to estimate the dust lofted by continental bursts.

These considerations of source mechanisms suggest that the mass of particulates lofted to stabilization altitude by surface bursts would be a few times 0.1 Tg/Mt.

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The 6,500-Mt baseline case included 400 weapons of 1 Mt or greater and 2,000 smaller weapons averaging 0.5 Mt detonated as surface bursts, presumably against hard targets such as silos and buried command structures.

... 

The ranges of lofted dust are assumed to arise only from the plausible range of 0.2 to 0.5 Tg/Mt for the lofting capabilities of the nuclear clouds. The most probable value of the lofted dust is 0.3 Tg/Mt, resulting in an estimated 15 Tg of stratospheric submicron dust. If the uncertainty in the submicron dust fraction is included, the overall range of uncertainty of potential dust injections increases further.

The mass of submicron dust lofted into the stratosphere in the baseline case is relatively small (10 to 24 Tg) in comparison with masses in the case studies by Turco et al. (1983). Contributing to this difference are the smaller weapon yields and the reduced total megatonnage in surface bursts that have been assumed in the baseline case.
The committee considered excursions that might increase the role of dust in postwar climatic effects. The main, 8,500 Mt, excursion adds 100 20-Mt surface bursts that might be used in attacks on superhard targets. The clouds from such bursts would reach 37 km (top) and 19 km (bottom), so that virtually all the lofted dust would reach the stratosphere. The lofted mass would be 400 to 1,000 Tg (600 Tg likely), with 8 percent of the mass in the submicron fraction.

The committee also considered a simultaneous attack totaling 500 Mt of surface bursts against a cluster of closely spaced hard targets. As discussed earlier, the rise of the resulting giant fireball would be qualitatively different from the rise of single-megaton buoyant fireballs. The rise rates are much greater (kilometers per second, instead of 100 m/s), so that the lofting efficiency might exceed the energy-constrained maximum of 2.6 Tg/Mt expected for buoyant fireballs. For example, the impact proposed by Alvarez et al. (1980, 1982) to explain the iridium-enriched Cretaceous-Tertiary (K-T) boundary claystone apparently lofted a total of $10^7$ Tg ($10^{19}$g) of dust. If the 10-km diameter impactor had a velocity of 30 km/s, its kinetic energy would have been about $10^8$ Mt. Most of this energy was deposited in the target material, but perhaps 5 percent ($5 \times 10^6$ Mt) appeared as thermal energy of the vaporized projectile and target material (Jones and Kodis, 1982). The explosive expansion of this high-pressure gas created an enormous fireball that was unconfined by the atmosphere and probably provided the energy to spread the dust worldwide. The implied lofting efficiency of the Cretaceous-Tertiary fireball is roughly 2 Tg/Mt. If this efficiency is used for the 500-Mt fireball in the postulated simultaneous attack, the mass lofted to very great altitude (perhaps 100 km; C. E. Needham, S-Cubed, Inc., Albuquerque, unpublished numerical simulations of 500-Mt explosions, 1982) would be about 1,000 Tg. This value is comparable with the dust lofted by the 100 20-Mt bursts in the 8,500 excursion.

The mass of submicron dust lofted into the stratosphere during a nuclear war would depend most critically on the following factors: (1) the number and individual yields of weapons used in surface bursts, (2) the lofting efficiency of the fireballs, and (3) the size distribution of particles in the stabilized cloud.

... Moreover, rapid spreading of particulates into the tropics and even into the southern hemisphere is a real possibility. These conclusions are contingent upon the assumptions that a substantial fraction of the smoke particles produced by burning cities would survive early scavenging and coagulation, and that subsequent aging and scavenging processes would not remove submicron smoke particles distributed throughout the middle and upper troposphere at a removal rate greater than about (2 weeks)$^{-1}$. Because of optical saturation due to the high absorptivity of smoke, the climatic effects are likely to be insensitive to moderate changes in smoke or absorptivity about the baseline values. However, lower values of either of these quantities by a factor of about 4 would lie near the edge of the saturation regime, and climatic effects would decrease rapidly for large reductions. Climatic effects are also sensitive to the removal rate of smoke. If middle and upper tropospheric rates were as large as (1 week)$^{-1}$ temperature perturbations would be considerably moderated although still significant. Improvements in the models are needed, particularly to investigate
further the effects of realistic transport and dispersion of smoke and dust in the perturbed atmosphere, the infrared opacity of the smoke, diurnal and seasonal effects, and the possible roles of ground fog and stratus and of ultra-high clouds forming at the top of the convective layer that may be driven by absorption of solar radiation in smoke and dust clouds. Long-term effects arising from possible changes in the properties of the underlying surface also require further study.

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VI. CHEMICAL CHANGES IN THE ATMOSPHERE

From: Global Consequences of Nuclear War and the Developing Countries, report by the Committee of Soviet Scientists for Peace, against the Nuclear Threat, Moscow, June 1984, p. 17.

"A huge amount of nitrogen oxides will be released during high-altitude powerful nuclear explosions in the atmosphere. Their content will increase several times over the normal level and they will bind atmospheric ozone. After the smoke disperses, the intensity of deadly ultraviolet radiation reaching the Earth's surface is going to increase approximately 2.5 times due to the destruction of the ozone layer. Radiation sharply increases as the ozone layer disintegrates. If only 10 per cent of ozone is left, the deadly irradiation dose will accumulate in the middle latitudes within a year while in the tropics it develops during the light hours of just one day. The peoples of the tropical countries will find themselves between the anvil of frosts and the hammer of deadly ultraviolet rays.

* * *


"... The analysis shows that explosive force of $10^4$ Mt would destroy 30-60 per cent of the total amount of ozone in the northern hemisphere. High injection rates are likely to considerably enhance the concentration of ozone below the level of injection owing to an increase in ultraviolet radiation caused by the destruction of the ozone in the upper layers of the stratosphere.

... The large-scale spread of radioactive products affects ecosystems by radiation and changes in electrical characteristics of the atmosphere. The pollution of the atmosphere by radioactive products and dust alters the radiation characteristics of the atmosphere, changes weather and climate, and causes deterioration of ecosystems because of the reduction of solar radiation. The climate is also affected by
changes in the gas composition of the atmosphere brought about by nitric oxides, ozone, methane ethylene and the formation of tropospherical ozone and other gases which significantly affect the thermal exchange in the atmosphere. Changes in the albedo (radiation reflection capacity) of the Earth's surface owing to fires can also cause changes in climate.

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tissues such as eyes, nose, throat and lungs. Formation of these harmful products in surface air may be at least initially suppressed by the reduction of available sunlight due to dust and smoke clouds in the troposphere and stratosphere. The duration of this reduction of available sunlight is an important issue.

A second major set of chemical reactions operate in the stratosphere to control the concentration of ozone (Crutzen, 1979; National Research Council, 1982) which is normally present in much higher concentrations in the middle stratosphere than in the troposphere. The amount of ozone in a vertical column largely controls the intensity of solar ultraviolet radiation in the biologically damaging wavelengths (known as UV-B radiation) which produce sunburn, skin cancers and damage to the cornea of the eye (leading to cataracts and blindness). At the temperatures and ultraviolet radiation levels which prevail in the stratosphere additional oxides of nitrogen lead to a reduction in ozone concentration. The introduction of bomb- or combustion-generated oxides of nitrogen into the stratosphere will lead to reductions in the ozone column amounts and to increases in UV-B intensities at the surface. Again, this effect at the surface would initially be offset by the presence of absorbing dust and smoke layers in the troposphere and/or stratosphere so the lifetime of these absorbing layers is critical.

The third major chemical consideration is the process by which fine particles are generated in situ by gaseous contaminants. This process operates naturally after major volcanic eruptions such as the El Chichón eruption in Mexico in April 1982. This process leads to the continuing formation of small particles, replacing those lost by coagulation and subsequent gravitational fallout, and could be important in prolonging the lifetime of absorbing layers in the stratosphere.

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"The dramatic restructuring of the Earth's atmosphere by injected aerosols moves the lower atmosphere towards isothermality and the upper atmosphere towards a major thermal inversion, as shown in our Science paper. In a fully interactive calculation, this restructuring would significantly prolong the duration of the climatic effects following a nuclear war. The snow/albedo and sea ice/thermal inertia feedback effects also act to extend the duration of nuclear winter.

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