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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.

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ANNEX

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

CONTENTS

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

atm	atmosphere (measurement of air pressure)
C	Centigrade
C^3	Command, control and communications
C^3I	Command, control, communications and intelligence
Cal (cal)	calorie
Ci	Curie
cm	centimetre
CO	carbon monoxide
CO_2	carbon dioxide
Cs	cesium
EPA	United States Environmental Protection Agency
g	gram
g/au^2	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)

NH	Northern hemisphere (North hemisphere)
N	nitrogen
NO	nitric oxide
NO_x	Odd nitrogen oxides - NO and NO_2
PAN	Peroxyacetyl nitrate
pH	potential of hydrogen
ppbv	parts per billion by volume
ppmv	parts per million by volume
psi	pounds per square inch
rads	The absorbed dose of any nuclear radiation which is accompanied by the liberation of 100 ergs of energy per gram of absorbing material
S	South
SCOPE	Scientific Committee on Problems of the Environment (ICSU)
SH	Southern hemisphere
Sr	strontium
Tg	teragram = 10^{12} grams
TTAPS	Turco, Toon, Ackerman, Pollack and Sagan
u (um)	micron
UV (uv)	ultra-violet
UV-B radiation	biologically damaging ultra-violet radiation
yr	year

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."

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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.

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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 TTAPS, 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 1985, 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.

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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.

From: "The World After Nuclear War", Conference on the Long-Term Worldwide Biological Consequences of Nuclear War, 31 October to 1 November 1983, Washington, D.C., Summary of Conference Findings, pp. 2-3.

"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.

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From: <u>Nuclear Winter and Associated Effects, A Canadian Appraisal of the Environmental Impact of Nuclear War</u>, report of the Committee on the Environmental Consequences of Nuclear War, The Royal Society of Canada, 31 January 1985.

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

(i) those in which variation of perturbance 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.

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From: "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions", by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and Carl Sagan, in <u>Science</u>, vol. 222 (23 December 1983), pp. 1283-1284. 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 um 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 1×10^5 to 6×10^5 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.

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From: "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, the journal of the Royal Swedish Academy of Sciences, vol. 13, No. 4, 1984.

"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 perturbaton 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, those 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 averge 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.

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From: The Effects on the Atmosphere of a Major Nuclear Exchange, report of the Committee on the Atmospheric Effects of Nuclear Explosions, National Research Council, National Academy of Sciences, Washington, D.C., 1985.

"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 faction 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 (C^3I) 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 C^3I 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/cm^2. 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 latitutes 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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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, 31 January 1985, pp. 17, 64, 65.

"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.

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Quantitive 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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From: <u>The Potential Effects of Nuclear War on the Climate</u>, a report of the Secretary of Defense to the United States Congress, United States of America, March 1985.

"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.

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

From: "The Atmosphere after a Nuclear War: Twilight at Noon" by Paul J. Crutzen and John W. Birks, in Ambio, the journal of the Royal Swedish Academy of Sciences, vol. 11, No. 2-3, 1982.

"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 $1.8 \times 10^5 km^2$ in the early 1930s to less than $1.6 \times 10^4 km^2$ 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 $0.4\text{-}6 \times 10^6 km^2$ 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 $2.2 \times 10^{16}g$ dry matter or about $10^{16}g$ 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 $2.5 \times 10^{15}g$ of carbon would be released to the atmosphere. During wildfires about 75kg of particulate matter is produced per ton of forest material burned or 450kg of carbon, so that $4 \times 10^{14}g$ 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 $1.8 \times 10^4 km^2$, which delivers $3.5 \times 10^{12}g$ particulate matter to the atmosphere. Accordingly, a total area of $10^6 km^2$ would inject $2 \times 10^{14}g$ particulate matter into the atmosphere which should come from $3 \times 10^{15}g$ of burned forest material, or $1.3 \times 10^{15}gC$. This is a factor of two less than the earlier derived estimate, so we will use a range of $1.3\text{-}2.5 \times 10^{15}g$ of carbon as the global atmospheric gaseous release and $2\text{-}4 \times 10^{14}g$ 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 $7 \times 10^{17}g$ 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 $2\text{-}4 \times 10^{14}gC$, 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

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_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 x 10^{14}g of particulate matter from the burning of 10^6km^2 of forests is comparable on a volume basis to the total global production of particulate matter with diameter less than 3 microns (um) 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 um and a maximum particle number density at a diameter of 0.1 um. 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_s(m), is related to the smoke density, d (g/m^3), by the relationship b_s = ad, where a is approximately 4-9m^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 x 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^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 x 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 way. 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 x 10^6m^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_2S) 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 x 10^{10}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 x 10^6 barrels of oil per day from a total of 390 wells (about 40 platforms) in the North Sea.

Considering that a 100-kt 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 8.6×10^6 barrels of oil per day from about 530,000 wells whereas the USSR production was 12.1×10^6 barrels per day from only 80,000 wells. The oil and gas fields of the Soviet Union, particularly the oil producing Volba-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 oilspill. 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 NO_x emissions from oil and gas field fires with those provided by current industrial rates. This adds 20 Tg of nitrogen to the NO_x source from forest fires.

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From: "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions", by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and C. Sagan, in Science, vol. 222 (23 December 1983), pp. 1284-1286, copyright 1983 by the American Association for the Advancement of Science.

"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 x 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 x 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 km^2 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/cm^2 (versus 10 g/cm^2 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 1×10^8 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 4×10^7 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.

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From: "The Climatic Effects of Nuclear War", by Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan, in Scientific American, vol. 251, No. 2 (August 1984), pp. 37-38.

"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

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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 aluminimum 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.

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From: <u>The Effects on the Atmosphere of a Major Nuclear Exchange</u>, report of the Committee on the Atmospheric Effects of Nuclear Explosions, National Research Council, National Academy of Sciences, Washington, D.C., 1985.

"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 <u>et al</u>., 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/cm^2 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 km^2/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 pyrolize 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:

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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 km^2/Mt (Ayers, 1965), which corresponds to thermal fluences of more than or of the order of 10 cal/cm^2. 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 m^2 (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 (1.5×10^{14} 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 um and y = 2.0; the effective particle density is 1 g/cm^3. The smoke infrared extinction and absorption coefficients (at 10 um) 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 5×10^{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 intial 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.

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* For volume-equivalent spherical particles.

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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/cm^2 and 4 g/cm^2. 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 km^2 (about 50 percent of the city cores of the combatant nations), consume 20 g/cm^2 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 aspects of the light transmission problem are discussed in Chapter 7.

Turco <u>et al</u>. (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.

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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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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, 31 January 1985.

"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).

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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From: "Global consequences of a nuclear war: a review of recent Soviet studies", by A. S. Ginsburg, G. S. Golitsyn and A. S. Vasiliev, in Global Armaments and Disarmament, SIPRI Yearbook, 1985.

"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 perceptibily 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 km^2 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.

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/m^2. 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/m^2; in cedar woods it is 0.2-1.1 kg/m^2; in broad-leaved forests the fallen dry matter is nearly 0.3 kg/m^2. The stock of dry combustible material in the timber of, for example, pine woods totals from 8 to 30 kg/m^2. In forests of low productivity, the stocks of dry material are not large -- just below 1 kg/m^2. The average stock of dry timber is about 15 kg/m^2.

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/m^2. 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 km^2 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.

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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 a 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.

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V. DUST AND SOOT

From: "Global consequences of a nuclear war: a review of recent Soviet Studies", by A. S. Ginsburg, G. S. Golitsyn, and A. S. Vasiliev, in Global Armaments and Disarmament, SIPRI Yearbook, 1985.

"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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From: "The Climatic Effects of Nuclear War", by Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan, in Scientific American, vol. 251, No. 2 (August 1984), pp. 35-39 and 41-43.

"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 attentuation 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.

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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 draft 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 base-line 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.

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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 states. 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.

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.

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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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From: "Global Atmospheric Effects of Massive Smoke Injections from a Nuclear War: Results from General Circulation Model Simulations", by Curt Covey, Stephen H. Schneider and Starley L. Thompson, in <u>Nature</u>, vol. 308 (1 March 1984).

"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.

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 2×10^{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, firestorms), 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 2×10^{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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From: "Some Changes in the Atmosphere over Australia that may Occur due to a Nuclear War", by I. E. Galbally, P. J. Crutzen and H. Rohde, published in Australia and Nuclear War, Michael Denborough, ed. (Croon Helm, Sydney, Australia, 1983), pp. 165-166, 167-169 and 169-173.

"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 10^7kg) of submicron material are produced per 1000 kiloton nuclear yield. This is consistent with Izrael 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 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 1.5×10^4 km^2 in the Southern Hemisphere and 2 to 6×10^5 km^2 in the Northern Hemisphere.

The total aerosol production during the initial exchange is approximately $10 \times 10^{12}g$ in the Southern Hemisphere and $200 \times 10^{12}g$ 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 1×10^9 m^2. The Ambio Scenario has around 200 targets in the Southern Hemisphere and perhaps 5500 in the Northern Hemisphere, and these 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 <u>Ambio</u> 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 <u>Ambio</u> 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).

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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.

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 bouyant 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 u radius (see Friedlander 1977, p. 135). The predominant size particles in fresh smoke is 0.05 u radius. It takes 125 particles of 0.05 u radius to make up the volume of one 0.25 u 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 10^4 particles/cm^3 with a peak number density of 0.05 u 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 occurence 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 faction 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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From: "Atmospheric Effects From Post-Nuclear Fires", by Paul J. Crutzen, Ian E. Galbally and Christoph Brühl, in Climatic Change, vol. 6, 1984. Copyright 1984 by D. Reidel Publishing Company, Dordrecht, Holland.

"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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From: *The Effects on the Atmosphere of a Major Nuclear Exchange*, report of the Committee on the Atmospheric Effects of Nuclear Explosions, by the National Research Council, National Academy of Sciences, Washington, D.C., 1985.

"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 um) 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.) Lofting 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).

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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.

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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 Butkovich (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/cm^3) and approximately

0.06 Tg/Mt for a porous dry soil or a very porous dry rock target (density of 1.4 g/cm^3).

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.

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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.

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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 stablization altitude in the fireball from a surface burst on a strong rock target.

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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.

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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 10^8Mt. Most of this energy was deposited in the target material, but perhaps 5 percent (5×10^6Mt) 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.

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... 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 $(2 \text{ weeks})^{-1}$. 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 $(1 \text{ week})^{-1}$ 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 dispels, 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.

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From: "On the Influence of Nuclear Explosions in the Atmosphere on the Ozone Content in the Stratosphere", by Y. Izrael, V. N. Petrov and D. A. Severov, in Meteorologia i Hydrologia, No. 9 (1983), pp. 5-13.

"... 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.

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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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From: "Long-Term Biological Consequences of Nuclear War", by Paul R. Ehrlich et al., in Science, vol. 222 (23 December 1983), pp. 1293-1300. Copyright 1983 by the American Association for the Advancement of Science.

"In a nuclear war, large quantities of air pollutants, including CO, O_3, NO_x, cyanides, vinyl chlorides, dioxins, and furans would be released near the surface. Smog and acid precipitation would be widespread in the aftermath of the nuclear exchange. These toxins might not have significant immediate effects on the vegetation that was already devastated, although, depending upon their persistence, they could certainly hinder its recovery. Their atmospheric transport by winds to more distant, initially unaffected ecosystems, on the other hand, might be an important additional effect. Large-scale fires coupled with an interruption of photosynthetic CO_2 uptake would produce a short-term increase in the atmospheric CO_2 concentration. The quantity of CO_2 now in the atmosphere is equivalent to that used by several years of photosynthesis and is further buffered by the inorganic carbon reserves of the ocean. Therefore, if the global climate and photosynthetic productivity of ecosystems recovered to near-normal levels within a few years, it is unlikely that any significant long-term change in the composition of the atmosphere would occur. It is not beyond the realm of possibility, however, that an event encompassing both hemispheres, with the ensuing damage to photosynthetic organisms, could cause a sudden increase in CO_2 concentration and thus long-term climatic changes. For comparison, the time scale for recycling of O_2 through the biosphere is about 2000 years.

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From: "The Atmospheric Effects of Nuclear War", by A. Barrie Pittock, in Australia and Nuclear War, Michael Denborough, ed. (Croon Helm, Sydney, Australia, 1983), pp. 145-146.

"Several major sets of atmospheric chemistry processes are relevant to the problem of the impact of nuclear war. One is the tropospheric set of reactions best known in relation to photochemical smog situations (Calvert, 1982). Chief ingredients in these tropospheric reactions are oxides of nitrogen, both generated by the nuclear explosions themselves and by subsequent fires, and hydrocarbons produced by incomplete combustion in urban, rural and oil or gas fires, or released by the evaporation of oil spills and natural gas leaks. These will react in the presence of sunlight to produce abnormally high concentrations of ozone and other noxious chemicals which are damaging to delicate plants and sensitive animal

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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 troposhere 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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From: "'Nuclear winter' to be taken seriously", by Richard Turco, O. B. Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan, in Nature, vol. 311 (27 September 1984), p. 307.

"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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From: "Some Changes in the Atmosphere over Australia that may Occur due to a Nuclear War", by I. E. Galbally, P. J. Crutzen and H. Rohde, in Australia and Nuclear War, Michael Denborough, ed. (Croon Helm, Sydney, Australia, 1983), pp. 173-179.

"The effects of this hypothetical nuclear war on stratospheric ozone, on radioactivity and on the acidity of rainwater are also evaluated. All these evaluations are based on the assumption of an unperturbed atmospheric circulation and the absence of the aerosol clouds already discussed.

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Ozone absorbs incoming solar radiation of wavelength shorter than about 320 nm, and thus shields the earth's surface from biologically damaging ultraviolet radiation. A change in the ultraviolet radiation reaching the earth's surface due to a change in the amount of ozone could have undesirable effects on those biological systems that are exposed to sunlight. In addition, ultraviolet as well as infra-red absorption by ozone plays an important role in determining atmospheric temperatures and climate.

The actual distribution of ozone in the atmosphere is determined by the combined effects of its production and destruction processes (including temperature - and radiation - induced variations) along with atmospheric transport processes. Hence the only way that the theory and observations of atmospheric ozone can be compared is by means of complex numerical simulation of all the processes involved.

Nitric oxide is produced by nuclear weapons by the heating of air in the interior of the fireball and in the shock wave (Gilmore 1975). This nitric oxide is mixed throughout the nuclear cloud. The cloud, for bombs with total yields of 1 Mt or greater, penetrates the tropopause depositing a substantial amount of NO in the stratosphere. At heights above 20 km this NO is expected to cause ozone depletion.

The clouds from bombs of total yield smaller than 1 Mt do not penetrate deep into the stratosphere and so for a given total megatonnage of weapons a shift towards smaller weapon size decreases the effect on stratospheric ozone whereas an increase in individual weapon size increases the effect on stratospheric ozone. This factor is important in understanding differences between the various assumed scenarios (Whitten, Borucki and Turco 1975; NAS 1975; Crutzen and Birks 1982).

It is not expected that there would be any significant direct effect of nuclear weapons exploded in the Southern Hemisphere on the ozone layer. The 173 Mt of weapons exploded in the Southern Hemisphere in the Ambio Scenario I (see Crutzen and Birks 1982) is smaller than the 300 Mt of mainly high yield bombs used in atmospheric tests by the US and USSR in 1961 and 1962. There has been considerable debate as to whether these bombs produced an ozone decrease of a few per cent (Chang, Duewer and Wuebbles 1979). Because of the large scatter in ozone measurements and our lack of understanding of all of the natural causes of ozone fluctuations, it has not been possible to unequivocally identify an ozone decrease due to these weapons tests. Thus the direct effect on the stratosphere of the

175 Mt allocated to the Southern Hemisphere in the Ambio Scenario I would probably be undetectable irrespective of the yields of the weapons used.

Crutzen and Birks (1982) consider the influence on stratospheric ozone of nitrogen oxides injected into the stratosphere from two different war scenarios. In Ambio Scenario I, the weapons are primarily low yield and no significant ozone depletion occurs. However, in the Scenario II, where high yield weapons are used there is massive injection of NO_x into the Northern Hemisphere stratosphere, perhaps twenty times the natural level, and we must consider the effect of this and its spread to the Southern Hemisphere.

Model studies of ozone depletion from this type of scenario have been carried out by Whitten et al. (1975), Chang (see NAS 1975) and more recently by Crutzen and Birks (1982).

Crutzen and Birks (1982) two-dimensional model predicts a rather uniform 65 per cent depletion of the ozone column spread from 45°N to the North Pole by the 50th day following the war. The depletions become less toward the equator and beyond, being 57, 42, 26, 12 and 1 per cent at 35°N, 25°N, 15°N, 5°N and 5°S, respectively. As time progresses, the ozone depletions become less in the Northern Hemisphere, but NO_x is transported to the Southern Hemisphere and causes significant depletion there. Two years following the war in the Northern Hemisphere the ozone column depletions vary uniformly from 15 per cent at 5°N to 66 per cent at 85°N, with a 39 per cent depletion of the ozone column at 45°N. At the same time ozone column depletions range from 12 per cent at 5°S to 18 per cent at 85°S in the Southern Hemisphere.

There are some important uncertainties in these model calculations. Along with the nitrogen oxides, large quantities of water vapour and particulates will be injected into the stratosphere. These particulates could have some minor role in contributing to the ozone destruction chemistry. This cannot at present be quantified. More importantly if the particulates are light absorbing they will contribute to the local heating of the stratosphere. Ozone depletion will, of course, lead to local cooling. Some of the ozone destroying reactions are dependent on temperature so these changes in heating rates are important. Furthermore the circulation of the stratosphere is driven by latitudinal and vertical differences in heating and cooling rates. A thick layer of light absorbing aerosol in the lower stratosphere would affect the dynamics of the stratosphere, the temperature of the stratosphere, the distribution of ozone destroying pollutants and ozone depletion in complex ways which we cannot predict. We can be confident, however, that the perturbation in the ozone column of the Northern Hemisphere would be quite large for a Scenario II nuclear war. The magnitude of the effect in the Southern Hemisphere is more uncertain.

The effect at the earth's surface in the Southern Hemisphere of a 10 per cent ozone decrease has been calculated by Paltridge and Barton (1978) and Stordal, Hov and Isaksen (1982) to be in the range of a 20-30 per cent increase in biologically damaging ultraviolet radiation (UV-B). The expected adverse effects of increased levels of UV-B include increased incidence of skin cancer in fair skinned races, decreased crop yields and variety of stresses on terrestrial and aquatic ecosystems (NAS 1979).

One factor which could mitigate these stresses from UV-B is the presence of enhanced levels of atmospheric aerosol from the nuclear weapons and subsequent fires. Evans et al. (1977) observed a 20 fold decrease in total UV radiation (direct plus diffuse) under a smoke plume that had an optical depth for scattering of $T_{scatt.} = 1.6$. Obviously a minor, but persistent enhancement of atmospheric aerosol in the Southern Hemisphere could mitigate the UV-B stress on biological systems. Similarly a persistent doubling of troposphere ozone (Crutzen and Birks 1982) would negate the effects of a 10 per cent decrease in stratospheric ozone. However these effects would have to last for as long as the ozone depletion and such a coincidence is unlikely.

Another effect of such a war is the introduction of radioactive material into the atmosphere from the fission material in the bombs and also from any nuclear facilities attacked in the war (Advisors 1982). We examine here the deposition of delayed fallout (that which occurs after 24 hrs) over Australia and from this hypothetical nuclear war. The deposition in the Northern Hemisphere has been extensively examined elsewhere (Ambio 1982).

A certain fraction of the radioactive material introduced into the NH atmosphere during a nuclear war will eventually find its way across the equator and be deposited in the Southern Hemisphere. Because of the time it takes to mix air from one hemisphere into another - several months - we need only concern ourselves with nuclides with a half-life comparable to or longer than this time scale. In the following estimate we concentrate on ^{90}Sr (Half-life 28 years) for which there exists fallout data from the nuclear bomb test period. ^{90}Sr is also important because of its tendency to accumulate in certain parts of the human body (bones and marrow).

As a basis for the calculations we make the following assumptions:

1. Only that fraction of the radioactivity that resides in the stratospheric portion of the stabilized bomb clouds is available for transport across the equator; the tropospheric portion of the Northern Hemisphere emission is assumed to be deposited -- mainly by precipitation -- before the air can reach the Southern Hemisphere.

2. The deposition of the stratospheric fraction is assumed to be distributed between the latitude bands similar to the observed distribution of ^{90}Sr in soils a few years after the bomb test period in the late fifties and early sixties (Hardy, Meyer, Allen and Alexander 1968).

3. The tropospheric fraction (excluding the local fallout) of the Southern Hemisphere bomb emission is assumed to be deposited uniformly between the equator and 45°S.

With these assumptions and with due regard to the radioactive decay the following deposition values result. Ambio's Scenarios I would result in an increase in the average ^{90}Sr deposit of about a factor of five. If, in addition, all nuclear reactors were hit, each by a 1 Mt bomb, the ^{90}Sr deposition would rise by another factor of 6. ... Substantial deviations are expected to occur mainly in connection with differences in precipitation amounts. The relation between the ^{90}Sr deposit in Southern Hemisphere soil samples during 1965-1967 and the average annual precipitation has been examined. Despite a considerable scatter in the date, probably partly due to deviations from average rainfall during the particular years in question, a higher deposit is associated with high average rainfall.

We estimate that certain high rainfall areas may receive at least a factor of three higher deposits than those indicated above. For the Scenario that includes nuclear reactors certain sites -- particularly in the mountain regions on the east coast of Australia -- may thus receive a ^{90}Sr deposit of roughly 1 Ci/km^2.

The deposition of ^{137}Cs would be similar but 50 per cent higher than that of ^{90}Sr (because of a higher yield of ^{137}Cs in the fission process).

Considerable amounts of sulfur and nitrogen oxides will be introduced into the atmosphere as a result of the fires during a large scale nuclear war. These oxides, particularly when further oxidised to sulfuric and nitric acid, will tend to make aerosols, cloud droplets and precipitation water acidic. In the bomb clouds from surface bursts the acidity so produced will be neutralised to a certain degree by alkaline material, e.g. calcium carbonate and metal oxides originating from the surface. The sulfur and nitrogen oxides emitted by the subsequent fires in urban areas, forests and oil and gas wells are less likely to be neutralised in this way.

We have made rough estimates of the acidity of precipitation during the weeks and months following the Ambio Scenario war. The following assumptions are made:

1. Thirty per cent of oxides are deposited by direct uptake at the surface without prior oxidation to sulfuric nitric acid. The remaining 70 per cent is deposited as acid in precipitation.

2. No neutralisation of these acids takes place in the atmosphere (this is a worst case assumption).

3. The deposition by precipitation of the sulfur and nitrogen emitted in association with the war will take place in the same latitude belt as the emission within two weeks of the emission.

4. Natural processes alone would maintain a pH in rainwater of about 5, as they do now.

We distinguish between short term emissions, i.e. those taking place during the first few days after the war and longer term emissions taking place during the first six months. The emissions are calculated on the same basis as aerosol emissions using the relevant emission factors. For long term emissions we add an additional source for burning oil and gas wells based on the assumptions made in Crutzen and Birks (1982).

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As with radioactivity, certain regions within these belts may receive rain with elevated contamination. This rain may have a pH value several tenths of a unit lower than the zonal average values. These pH values are more acidic than those experienced in some industrialised regions of the earth (Rodhe 1981).

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From: The Effects on the Atmosphere of a Major Nuclear Exchange, report of the Committee on the Atmospheric Effects of Nuclear Explosions, National Research Council, National Academy of Sciences, Washington, D.C., 1985, pp. 107-123.

...

"Effects of Emissions

"Ozone Shield Reduction

"The first perceived threat of stratospheric ozone by pollutants implicated the oxides of nitrogen (NO and NO_2, known collectively as NO_x). At that time, the early 1970s, it was the prospect of supersonic flight that caused concern (see, e.g., NRC, 1973). Threats to the ozone layer from emissions of chloro fluorocarbons and from increases in nitrous oxide (N_2O) concentrations (caused by the increased application of nitrogen fertilizers) have been recognized and assessed (see, e.g., NRC, 1982). The problem of ozone reduction by N_2O increase is in essence the same as that of reduction by adding NO_x, since N_2O is converted to NO in the stratosphere. In 1975 the NRC conducted a workshop for the purpose of studying effects of large-scale nuclear detonations. Of all of the aspects addressed, that concerning the effects of NO_x injection received the most detailed treatment because of the recent awareness brought about by the SST studies (Crutzen, 1971; Johnston, 1971) and the work of Foley and Ruderman (1973), who pointed out that the NO_x produced in the fireballs of nuclear weapons should lead to ozone reduction (see ozone reductions from NO_x injections for various nuclear war scenarios) (Chang and Wuebbles, 1982; Crutzen and Birks, 1982).

The list of chemical reactions thought to describe the behavior of ozone in the stratosphere is long and imposing. The interactions of the various atoms and molecules among themselves and with sunlight and their further dependence upon atmospheric transport make up a very complicated system. Though much is known about this system and the ability to model it has increased considerably in the last decade, much uncertainty still remain attendant to the application of the models to such drastic perturbations as those in the baseline scenario. However, there is now a large body of evidence that concentrations of ozone in the present stratosphere are principally controlled by NO_x from natural sources. For this reason alone, it is expected that a large perturbation in the stratospheric burden of NO_x, particularly in the upper regions of the stratosphere, would result in a large decrease in the ozone column.

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The amount of ozone reduction caused by injection of NO into the stratosphere depends on the amounts of NO and their distribution with altitude, which in the case of a nuclear bomb depend upon the yield and height of burst. ... Thus the estimate of the ozone reduction that would result from a nuclear war depends on the yield, type of burst, and latitude, for each weapon of the scenario used. For the baseline scenario, concentrations of NO_x would be greatly enhanced in the lower stratosphere up to about 19 km.

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Since the model used in this study considers transport only in the verticle dimension, it cannot provide an estimate of the amounts of NO_x transported into the southern hemisphere. The ability of the atmosphere to transport trace substances across the equator in the stratosphere was demonstrated by many observations of radioactive debris from nuclear weapons testing in the atmosphere. The nature of this phenomenon was delineated by Mahlman and Moxim (1978) using a general circulation model. Their study, using a single mid-latitude tracer injection, showed that the maximum burden in the southern hemisphere occurred about 9 months after the injection and was less than 10 per cent of the initial amount injected. Crutzen and Birks (1982) calculated southern hemisphere ozone reduction to be of the order of 15 per cent occurring after the injection of somewhat higher amounts of NO_x than in the excursion case.

Ozone Holes and Effects of NO_2 Radiation Absorption

Luther (1983) has studied short-term chemical and radiative effects of injections of NO into the stratosphere by nuclear weapons. The particular problem he addresses is the "ozone hole". Rapid heating of portions of the stratosphere containing high concentrations of NO_2, with subsequent mixing throughout the heated and destabilized volume, causes the ozone hole, which is a large reduction in the ozone column abundance distributed over most of the vertical extent of the stratosphere, but confined laterally. Ozone holes would permit a very large increase in irradiance of ultraviolet light at the top of the troposphere, which, in the absence of smoke or clouds, would result in life-damaging effects at the surface. Luther's study assumed that the cloud remained cylindrical throughout the depths of the stratosphere and that horizontal mixing could be represented by eddy diffusion. These assumptions are probably not realistic, since the "filling" of the holes by shear in the vertical is likely to be rapid and effective. Thus, it is considered that the ozone holes would exist for no more than a few hours and their effects would be less severe than those from global-scale reductions.

Effects on Ozone of Past Nuclear Weapons Tests

In accordance with the committee's estimates, the approximately 300 Mt of total bomb yield in multimegaton atmospheric bursts by the United States and USSR in 1961 and 1962 introduced about 3×10^{34} additional molecules of nitric oxide into the stratosphere. Thus one might ask whether these tests resulted in a depletion of the ozone layer. Using a one-dimensional model, Chang <u>et al</u>. (1979) estimated that these nuclear weapons tests should have resulted in a maximum ozone column depletion in the northern hemisphere of about 4 per cent in 1963. Analysis of the ground ozone observational data by Johnston <u>et al</u>. (1973) showed a decrease of 2.2 per cent for the period 1960-1962 followed by an increase of 4.4 per cent in 1963-1970. Although these data are consistent with the magnitude of the ozone depletion expected, by no means is a cause and effect relationship established. Angell and Korshover (1973) attributed these observed ozone column changes to meteorological factors. The ozone decrease began before most of the large weapons had been detonated and persisted for too long a period to be totally attributed to recovery from bomb-induced ozone depletion. Unfortunately, because of the large scatter in the ground-based ozone observational data and our lack of understanding of all of the natural causes of ozone fluctuations, one cannot draw definite conclusions about the effects of nuclear explosions on stratospheric ozone on the basis of previous tests of nuclear weapons in the atmosphere.

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Tropospheric Composition Changes

Because the troposphere is in direct contact with the biosphere, it is especially important to understand the chemical changes that would take place in this region of the atmosphere following a nuclear war. The many fires ignited by the nuclear explosions would inject large quantities of carbon monoxide, hydrocarbons, and many other organic compounds into the atmosphere. Both fires and the nuclear explosions themselves would produce large quantities of oxides of nitrogen. In the presence of sunlight, these compounds react to form strong oxidants, particularly ozone and organic peroxides such as peroxyacetyl nitrate (PAN). PAN and related compounds have strong phytotoxic effects. Ozone, while being necessary in the stratosphere to serve as a shield against solar ultraviolet radiation, is considered undesirable at ground level because of its toxic effects on both plants and animals.

Whether or not a dense photochemical smog with high oxidant concentrations would form in the wake of a nuclear war is difficult to evaluate for several reasons. Perhaps the largest uncertainties are associated with (1) the extent and duration of the darkening caused by the smoke and dust, and (2) changes in tropospheric dynamics and precipitation rates, which in turn affect the lifetimes of the relevant chemical species.

It is not possible to make quantitative predictions of all the chemical composition changes of the troposphere following a nuclear war. However, it seems likely that the rate of oxidation of tropospheric species would be greatly decreased, particularly near the surface of the earth, for the period of time that the particulate matter resides in the atmosphere. Although oxidants in the atmosphere are usually looked upon as undesirable because of the damage they cause to plants and animals, oxidants serve an important function in cleansing the atmosphere of many anthropogenic and biogenic emissions. In fact, the lifetimes of nearly all compounds released to the atmosphere are determined by the rates of reaction with the hydroxyl radical.

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In addition to the increased burden of toxic chemicals as the result of nuclear war fires, one would expect large increases in the concentrations of many reduced compounds for two reasons: (1) the lifetimes of many compounds would be increased by large factors due to reduced concentrations of OH and other oxidants, and (2) biogenic emissions of some compounds might increase by large factors following a nuclear war.

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Because of the large heat capacity of the mixed layer of the ocean, the temperature of the ocean would be little changed. The principal effect of a nuclear war on biogenic emissions from the ocean would probably result from periods of low light intensity. Photosynthesis in the ocean takes place to a critical depth where the sunlight is attenuated to about 1 per cent of its normal incident light flux. The darkness following a nuclear war would shift this critical depth much closer to the surface. As a result, one might expect the death of a significant fraction of the phytoplankton and zooplankton of the northern hemisphere ocean following a nuclear war (Milne and McKay, 1982).

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Toxic Chemical Releases

In addition to the emissions of carbon monoxide, nitrogen oxides, and organic compounds produced by the pyrolysis and partial combustion of wood, several million tons of noxious chemicals would be released to the atmosphere as a result of the pyrolysis and partial combustion of synthetic polymers such as rubber, plastics, and synthetic fibers located in urban areas, and chemicals in industrial storage. These chemical releases could have severe local consequences in and near the heavily populated urban areas. Occasional accidental releases of noxious chemicals have resulted in temporary evacuations of large areas. Contamination of the ground at very low levels (one part per million and below) by some particularly toxic chemicals has caused the permanent evacuation of some areas (e.g., Love Canal, New York, and Times Beach, Missouri). Recent attention has been drawn particularly to the polychlorinated biphenyls (PCBs), dioxins, and chlorine-substituted dibenzofurans. In the United States alone, more than 300,000 tons of PCBs are in use in electrical equipment and approximately 10,000 tons in storage (S. Miller 1983). A large fraction of this toxic chemical could be released to the environment in a nuclear war. Apparently, dioxins and dibenzofurans may be produced in large quantities in the combustion of fuels containing chlorine, although this is currently a matter of considerable controversy (J. A. Miller, 1979; Bumb _et al_., 1980; _Chemical and Engineering News_, 1983).

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Pyrolysis and partial combustion of these and less abundant chemicals would result in the deposition of thousands of chemical species in the atmosphere and ultimately in the soil and water. The chlorine compounds would be expected to account for a large fraction of the more toxic, mutagenic, teratogenic, and carcinogenic compounds.

The problem of toxic chemicals released in a nuclear war is highly specific to locality and does not lend itself readily to general analysis. It seems likely, however, that portions of most of the urban areas affected would be seriously contaminated, at least in the smoky air during and immediately following burning. The possibility of serious local contamination of the ground and water for long times after the war cannot be ruled out.

Among the toxic materials released to the environment would be asbestos. The current world production of asbestos fibers amounts to about 4 million metric tons per year. More than 30 million tons (30 Tg) of asbestos has been accumulated in the United States alone. Accumulation by industrialized nations is in excess of 100 Tg. These fibers are bound in a wide variety of construction materials and other products. Much asbestos contained in the nonflammable materials would be released as the result of pulverization by the nuclear blast. Since asbestos fibers are nonflammable, they would also be released to the atmosphere upon combustion of materials such as floor tile and asphalt shingles.

It is difficult to estimate how much asbestos would be released to the atmosphere as the result of a nuclear war. However, when mixed uniformly throughout the lower 9 km of the atmosphere and over half of the northern hemisphere, the atmospheric concentration of asbestos is calculated to be about 0.3 fibers per cubic centimeter for each teragram of asbestos released. This calculation uses the conversion factor used in epidemiological studies in which it is assumed that 1 fiber would be detected by phase contrast light microscopy for every 30×10^{-12} g of suspended asbestos. An optical fiber is defined as any particle longer than 5 um, having a length-to-diameter ratio of at least 3-to-1 and a maximum diameter of 5 um. Of course, the actual number of fibers is much larger, owing to the preponderance of smaller fibers not counted. The present Occupational Safety and Health Administration (OSHA) standard for exposure to asbestos is a time-weighed average of 2.0 fibers per cubic centimeter over an 8-h period, and OSHA announced a decision to lower it to 0.5 fibers per cubic centimeter in November 1983. A recent NRC study (NRC, 1984) estimated the average nonoccupational exposure in the United States to asbestos to be 0.0004 fibers per cubic centimeter. Five teragrams (less than 5 per cent of the world accumulation) of asbestos released to the atmosphere would increase the general population exposure to asbestos by a factor of about 4000 for the period of time that the particles are suspended and uniformly distributed. Of course, the fibers would be subject to resuspension and would be concentrated in the boundary layer of the atmosphere.

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VII. EFFECTS AND CONSEQUENCES ON ATMOSPHERE AND CLIMATE: NUCLEAR WINTER

From: "The Atmosphere after a Nuclear War: Twilight at Noon", by Paul J. Crutzen and John Birks, in Ambio, the journal of the Royal Swedish Academy of Sciences, vol. 11, No. 2-3, 1982.

"For several weeks following the war the physical properties of the Northern Hemispheric troposphere would be fundamentally altered, with most solar energy input being absorbed in the atmosphere instead of at the ground. The normal dynamic and temperature structure of the atmosphere would therefore change considerably over a large fraction of the Northern Hemisphere, which will probably lead to important changes in land surface temperatures and wind systems. The thick, dark aerosol layer would likely give rise to very stable conditions in the troposphere (below 10 km) which would restrict the removal of the many fire-produced and unhealthy pollutants from the atmosphere. Furthermore, fires also produce as many as 6×10^{10} cloud condensation nuclei per gram of wood consumed. The effect of many condensation nuclei is to narrow the cloud droplet size distribution and suppress formation of rain droplets by coalescence, probably leading to a decrease in the efficiency with which clouds can produce rain. The influence of large-scale vegetation fires on weather has been recognized by researchers for many years. After the settling of most of the particulate matter, ozone concentrations over much of the Northern Hemisphere could approach 160 ppbv for some months following the war. With time, substantial increases in other pollutants such as PAN to several ppbv may also occur. These species are important air pollutants which are normally present in the atmosphere at much lower concentrations (-30 ppbv for ozone and less than 0.1 ppbv for PAN).

The effects of ozone on public health and plant growth have been studied for several decades, especially in the US in connection with the Los Angeles basin photochemical smog problem. The effects on agricultural plants may be particularly severe. A major EPA report, listed several examples of decreases in yields of agricultural crops. For instance: "A 30 per cent reduction in the yield of wheat occurred when wheat at antheses [blooming] was exposed to ozone at 200 ppbv, 4 hours a day for 7 days ... Chronic exposures to ozone at 50-150 ppbv for 4-6 hours a day reduced yields in soybeans and corn grown under field conditions. The threshold for measurable effects for ozone appear to be between 50 and 100 ppbv for sensitive plant cultivers ... An ozone concentration of 50 to 70 ppbv for 4 to 6 hours per day for 15 to 133 days can significantly inhibit plant growth and yield of certain species."

...

We conclude, therefore, that the atmospheric effects of the many fires started by the nuclear war would be severe. For the war scenario adopted in this study, it appears highly unlikely that agricultural crop yield would be sufficient to feed more than a small part of the remaining population, so many of the survivors of the initial effects of the nuclear war would probably die of starvation during the first post-war years. This analysis does not address the additional complicating adverse effects of radioactivity or synergism due to concomitant use of chemical and biological warfare weapons.

The described impacts will be different if a nuclear war starts in the winter months. Forest areas burned may be half as large, photochemical reactions would be slower because of less solar radiation and lower temperatures. However, in wintertime, because of the low sun, the darkness caused by the fire-produced aerosol would be much worse.

In this work little discussion could be devoted to the health effects of fire-produced pollutants. They too, no doubt, will be more serious in winter than in summer."

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From: "Some Changes in the Atmosphere over Australia that may Occur due to a Nuclear War", by I. E. Galbally, P. J. Crutzen and H. Rodhe, in Australia and Nuclear War, Michael Denborough, ed. (Croon Helm Press, Sydney, Australia, 1983).

"It appears that the greatest atmospheric environmental hazard accompanying a nuclear war is the attenuation of sunlight by smoke clouds generated by the fires from nuclear explosions. These calculations support and extend the previous work (Crutzen and Birks 1982) which concluded that at least in the northern hemisphere there could be 'twilight at noon'. We suggest that darkness may extend to the Southern Hemisphere. We believe that sophisticated model calculations are required to more thoroughly examine these possibilities."

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From: "The World After Nuclear War", Conference on the Long-Term Worldwide Biological Consequences of Nuclear War, 31 October to 1 November 1983, Washington, D.C., Summary of Conference Findings, pp. 4-5.

"Contrary to the conclusions reached in most earlier studies, nuclear war probably would have a major impact on climate lasting for several years. It would be manifested by a dramatic drop in land temperatures to subfreezing levels for several months, large disturbances in global circulation patterns, and dramatic changes in local weather and precipitation. Even if the war were to occur in the summer, many areas might be subject to continuous snowfall for months.

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Except for areas near coastlines, land temperatures would plunge from -15° C (+5°F) to -25° C (-13°F), with dire consequences for survivors. The impact of dramatically reduced temperatures on plants would depend on the time of year at which they occurred, their duration, and the tolerance limits of the plants. The abrupt onset of cold is of particular importance, though, since plants that normally can withstand subfreezing temperatures would have no time to develop tolerance. A spring or summer war would kill or damage virtually all crops in the Northern Hemisphere.

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Most uncultivated food sources also would be destroyed, as would most farm animals. Many animals that survived would die of thirst, as surface fresh water would be frozen over the interior of continents. Available food supplies would be rapidly depleted. Most of the human survivors would starve.

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Nations that now require large imports of foods, including those untouched by nuclear detonations, would suffer the immediate cessation of incoming food supplies. These countries would be forced to rely on their local agricultural and natural ecosystems. This would be especially serious for many less-developed countries, particularly those in the tropics.

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Exposure to radioactive fallout would be more widespread than is predicted by standard empirical exposure models because of the intermediate fallout which would extend over many days and weeks. With unprecedented quantities of fission debris released into the atmosphere, even areas remote from the explosion sites would be subject to large doses of fallout radiation.

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In the baseline case, roughly 30 per cent of the land at Northern mid-latitudes (30°N to 60°N) would receive a radioactive dose greater than 250 rads over several months. About 50 per cent of the Northern mid-latitudes would receive a long-term dose greater than 100 rads. (This dose includes radionuclides ingested from contaminated food.) These doses are roughly ten times larger than previous estimates. A 100 rad dose is the equivalent of approximately 1,000 medical x-rays. A 400 rad whole-body acute dose is usually considered lethal. Doses this large can affect the immune system and increase the probability of infectious disease, cancer and genetic and embryonic defects.

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Because the climate effects would not last longer than a few years, an Ice Age would probably not be generated. Subfreezing temperatures will freeze most freshwater systems to considerable depth, leaving survivors without surface water. The oceans will not freeze due to their enormous reservoir of heat. It has often been thought that the coastal areas would be a major source of food for survivors of a nuclear war. However, the combined effects of darkness, ultraviolet light, severe coastal storms due to enormous land-sea temperature differentials, run-off of silt and toxic chemicals from the land, destruction of ships and concentrations of radionuclides in fish and other marine life cast strong doubt on this contention.

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Increased levels of UV-B can harm biological systems in several ways. The immune systems of humans and other mammals are known to be suppressed by relatively low doses of UV-B. Given the conditions of increased radioactive fallout and other stresses, such suppression of the immune systems leads to an increase in the incidence of disease. Protracted exposure to increased UV-B also may lead to widespread blindness among humans and other mammals.

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Tropical plants are less able to cope with even short periods of cold and dark than those in temperate zones. If darkness or cold, or both, were to become widespread in the tropics, the tropical forests, which are the major reservoir of organic diversity, could largely disappear. This would, in turn, lead to the extinction of a majority of the species of plants and animals on earth.

...

The dependence of urban populations in many tropical and developing countries on imported food would lead to severe effects, even if those areas were not affected directly by the war. Large numbers of people would be forced to leave the cities and attempt to cultivate the remaining areas of forest, accelerating their destruction and the consequent rate of extinction. Regardless of the exact distribution of the immediate effects of the war, everyone on Earth would ultimately be profoundly affected.

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Relatively large climatic effects can result from small nuclear exchanges (100 to 1,000 Mt). A scenario involving 100 Mt exploded in the air over cities could produce a two-month interval of subfreezing land temperatures, with a minimum near -23°C. In this scenario thousands of fires would be ignited and the smoke from these fires alone would generate a period of cold and dark almost as severe as in the baseline (5,000 Mt) case.

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In the aftermath of a 5,000 Mt nuclear exchange, survivors would face extreme cold, water shortages, lack of food and fuel, heavy burdens of radiation and pollutants, diseases, and severe psychological stress -- all in twilight or darkness.

It is clear that the ecosystem effects <u>alone</u> resulting from a large-scale thermonuclear war would be enough to destroy civilization as we know it in at least the Northern Hemisphere. These long-term effects, when combined with the direct casualties from the blast, suggest that eventually there might be no human survivors in the Northern Hemisphere. Human beings, other animals and plants in the Southern Hemisphere would also suffer profound consequences.

The scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future.

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From: "The Biological Consequences of Nuclear War", by Paul R. Ehrlich, in The Cold and the Dark: the World After Nuclear War, W. W. Norton and Company, New York, 1984, pp. 47-50, 54-55 and 56-57.

"Reduced temperatures would have dramatic direct effects on animal populations, many of which would be wiped out by the unaccustomed cold. Nevertheless, the key to ecosystem effects is the impact of the war on green plants. Their activities provide what is known as primary production -- the binding of energy (through photosynthesis) and the accumulation of nutrients that are necessary for the functioning of all biological components of natural and agricultural ecosystems. Without the photosynthetic activities of plants, virtually all animals, including human beings, would cease to exist. All flesh is truly "grass".

...

The impacts of such low temperatures on plants would depend, among other things, on the time of year that they occurred, their duration, and the tolerances of different plant species to chilling. An abrupt onset of cold is particularly damaging. After a nuclear war, temperatures are expected to fall precipitously over a short time; thus it is unlikely that normally cold-tolerant plants could acclimate before they were exposed to lethal temperatures. Furthermore, even temperatures considerably above freezing can be damaging to some plants, and other stresses not shown in Table 1 (radiation, air pollution, low light levels) would intensify the damage to vegetation caused by chilling or freezing. In addition, diseased or damaged plants have a reduced capacity to acclimate to freezing.

What all this boils down to is that virtually all plants in the Northern Hemisphere would be damaged or killed in a war that occurred just prior to or during the growing season. Most annual crops would likely be killed outright, and there would also be severe damage to many perennials if the war were to occur when they were growing actively. Damage might, of course, be less if it happened during the season when they were dormant.

Before a fall or winter war, humanity's main food sources -- wheat, rice, corn, and other cereal grains -- would have been harvested. But the weather would probably remain unusually cold for months afterward, preventing growth during the next spring and summer, even if other conditions were suitable. Also, since winter temperatures would be far below normal minimums, many perennial plants (for example, fruit trees and important components of the natural vegetation) could be killed. The seed stocks of temperate plants, however, generally would not be damaged by the cold, although those of many tropical plants would be.

While a fall or winter war would probably have a less severe impact on plants at northern latitudes than a spring or summer one, it still could have a severe impact in the tropics, where plants grow throughout the year. The only areas in the Northern Hemisphere where terrestrial plants might not be devastated by severe cold would be in coastal zones and on islands where the temperatures would be moderated by the oceans. Coastal areas, however, would experience especially violent weather because of the enormous temperature differential that would develop between the land and the sea.

Cold, remember, is just one of the stresses to which green plants would be subjected. The blockage of sunlight that caused the cold would also reduce or terminate photosynthetic activities. This would have innumerable consequences that would cascade through food chains including those supporting human beings. Primary productivity would be reduced roughly in proportion to the amount of light reduction, even if the vegetation were not otherwise damaged. If the light level declined to 5 per cent or less of normal levels -- which is likely to be the case for months in the middle latitudes of the Northern Hemisphere -- most plants would be unable to maintain any net growth. Thus, even if temperatures remained normal, the productivity of crops and natural ecosystems would be enormously reduced by the blocking of sunlight following a war. In combination, the cold and darkness would constitute an unprecedented catastrophe for those systems.

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The Fate of Vertebrates and Soil Organisms

The disaster that would befall many or most of the plants of the Northern Hemisphere from the effects of a nuclear exchange would contribute to an equal or greater disaster for the higher animals. Wild herbivores and carnivores and domestic animals either would be killed outright by the cold or would starve or die of thirst because surface waters were frozen. Following a fall or winter war, many dormant animals in colder regions might survive, only to face extremely difficult conditions in a cold, dark spring and summer.

Scavengers that could withstand the projected extreme cold would likely flourish in the postwar period because of the billions of unburied human and animal bodies. Their characteristically rapid population growth rates could, after the thaw, quickly make rats, roaches, and flies the most prominent animals shortly after World War III.

Soil organisms are not directly dependent on photosynthesis and can often remain dormant for long periods. They would be relatively unaffected by the cold and the dark. But in many areas the loss of aboveground vegetation would expose the soil to severe erosion by wind and water. Soil organisms may not be terribly susceptible to the atmospheric aftereffects of nuclear war, but entire soil ecosystems are likely to be destroyed anyway.

Impacts on Agricultural Systems

Agricultural ecosystems would be subject to the same kind of impacts as natural ecosystems, but they deserve some extra attention because at present they support human populations far above the carrying capacities of natural ecosystems.

There is little storage of staple foods in human population centers, and most meat and produce are supplied by current production. Only cereal grains are stored in any significant quantities, but the storage sites are usually located in relatively remote areas. Thus, after a nuclear war, supplies of food in the Northern Hemisphere would be destroyed or contaminated, located in inaccessible areas, or quickly depleted. People who survived the other effects of the war would

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soon be starving. Furthermore, countries that now depend on large imports of foods, including those untouched by nuclear detonations, would suffer immediate and complete cessation of incoming food supplies. They would have to fall back on local agricultural and natural ecosystems. For many developing countries, this could mean starvation for large fractions of their populations.

Reestablishment of agriculture after the war would probably be very difficult. Most crops are highly dependent on substantial subsidies of energy and fertilizers. In addition, producing harvestable yields generally depends on the availability of full sunlight, adequate water, suppression of pests, and relative freedom from stresses such as air pollution and UV-B. Few of these requisites would be available in the immediate postwar world.

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The Fate of the Tropics

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Under any war scenario, the spread of cold and darkness to the extensive tropics of the Northern Hemisphere is highly likely, and it is at least possible that they would spread to the tropics of the Southern Hemisphere as well. Even if the darkness and cold were largely confined to the north temperate regions, pulses of cold air could penetrate well into the tropics. It is therefore appropriate to discuss the probable consequences of such a spread.

Many plants in tropical and subtropical regions do not possess dormancy mechanisms enabling them to tolerate cold seasons. In those regions, large-scale injury to plants would be caused by chilling, even if temperatures did not fall all the way to freezing. In addition, vast areas of tropical vegetation are considered to be very near the photosynthetic "compensation point" -- their uptake of carbon dioxide is only slightly more than that given off. If light levels dropped, those plants would begin to waste away -- even in the absence of cooling. If light remained low for a long time, or if low light levels were combined with low temperature, tropical forests could largely disappear, taking with them most of one of Earth's most precious nonrenewable resources: its store of genetic diversity, including the majority of plant and animal species. Tropical animals, including human beings, are also much more likely to die of the cold than their temperate counterparts. In short, where tropical regions are affected by climatic changes, the consequences could be even more severe than those caused by a similar change in a temperate zone.

Furthermore, even in the absence of cold and darkness, the dependence of tropical peoples on imported food and fertilizer would lead to severe problems. Large numbers of people would be forced to leave cities and attempt to cultivate remaining areas of tropical rain forest, accelerating their destruction as the systems were taken far beyond their carrying capacity.

The Fate of Aquatic Systems

Finally, what would happen to the parts of our planet that are covered with water? Aquatic organisms tend to be protected from dramatic fluctuations in air temperature by the slowness with which water changes its temperature. In general, therefore, aquatic systems should suffer somewhat less disruption than terrestrial ones. Nonetheless, many freshwater systems would freeze to considerable depths (or completely). After a nuclear war in the spring, for instance, three feet or more of ice would form on all bodies of fresh water, at least in the North Temperate Zone. This would even further reduce light levels in lakes, ponds, rivers, and streams in a darkened world. Oxygen would be depleted, and many aquatic organisms would be exterminated. Moreover, the depth of the freezing would make access to surface water by surviving people and other animals extremely difficult.

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From: Global Consequences of Nuclear War and the Developing Countries, report of the Committee of Soviet Scientists for Peace, against the Nuclear Threat (Moscow, 1984), pp. 14-16, 17-21 and 29.

"The upper layers of the polluted atmosphere facing the Sun will be heated more intensively than now and, as a result, the troposphere, the lower layer of the atmosphere in which temperature drops with height, will begin to disappear. The atmosphere will become superstable. Disappearance of the troposphere will suppress the vertical movement of water vapour, which drastically change the hydrological cycle of the atmosphere - severe cold drought will set in on the continents. The wash-out of nuclear dirt from the atmosphere will be slowed down considerably. It has to be expected therefore that in the conditions of heavy nuclear pollution natural self-purification of the atmosphere will also take place much slower than at present.

The ocean will cool off more slowly due to its immense thermal inertia. According to estimates, ten months after, the temperature of the ocean surface will decrease on average by about 1.2 degrees Centigrade. Therefore air over its surface will cool off by "merely" several degrees which, as a matter of fact, will be sufficient for the formation of a thick fog that will stay for a long time. The enormous temperature contrast between the cooled land and the slowly cooling ocean will produce severe storms accompanied by heavy snowfall along a wide coastal area. This means that, regardless of the season, a long "nuclear winter" will set in all over the globe.

Inside the continents rainfall will be close to zero, crops will be destroyed and those domestic animals which may survive the cold spell will die of thirst because fresh water will be frozen as a rule.

The rising temperature in the upper layers of the atmosphere will lead to the overheating of the high mountain ranges. Over the Tibet, for example, the air temperature is expected to rise by 20 degrees Centigrade 8 months after the conflict starts. That will result in a change in the hydrological conditions of mountain glaciers and snowfields, their intensive melting and, as a consequence, produce floods which may inundate entire countries.

The described effects are not likely to provoke another ice age, although the validity of this conclusion is not evident. The oceans will not freeze over because of their thermal inertia. However, coastal waters will fail to provide food because of severe storms, darkeness, ultraviolet radiation, toxic gases slipping down from the continents, the destruction of the fishing fleet, and radiative contamination of fish.

It should be pointed out that this optico-mechanical effect of shock drop in air temperature over land surface for a prolonged period constitues the main climatic consequences of a nuclear conflict.

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The death of tropical forests in a "nuclear winter" is bound to increase the reflectivity of the areas they occupy several times. And even after the atmosphere restores its original transparency, these areas will continue to receive much less energy from the Sun. As a result, the energy pattern of the Earth's climatic system will change qualitatively in the long run, and the climate, followed by the biosphere, will enter a new state whose features are difficult to predict. Evidently, this new state would be poorer above all in the higher forms of life and it looks as if man does not fit into the picture.

... The geography of the theatre of operations is also of little import. In the event of a global nuclear conflict climatic after-effects in the Northern Hemisphere will set in after a few days and in the Southern Hemisphere in a matter of weeks. In case of a local nuclear conflict in any spot of the globe air currents will spread nuclear dirt over the Northern Hemisphere in a matter of one month, and after another month the Southern Hemisphere will also be affected.

All this means whatever the scenario of a nuclear war survivors of the first strike will have to live in severe cold, sufferering from lack of water, food and fuel, exposed to powerful radiation, pollutants, and disease, under an extreme psychological stress - all that in twilight or even in darkness. Nuclear war would signify either the extinction of the human race or the degradation of the survivors to a state below the prehistoric level.

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Tropical forests, the main carriers of organic life and the main source of oxygen, will be destroyed even by a brief spell of cold and darkness since they can exist only within a narrow thermodynamic range and are incapable of sustaining sharp fluctuations in intensity of illumination or temperature. That is going to become an additional factor which alone would kill the greater part of the Earth's flora and fauna since the biosphere would be left without oxygen. And if some amount of oxygen does remain, its reserve will be exhausted by aerobic bacteria - mineralisers of the remnants of animals and plants. Even if the biosphere survives, its functioning will be greatly disturbed. The biosphere operates as an integral planetary mechanism which ensures assimilation of solar energy, carbon dioxide, water, and mineral substances by animals and microbes (consuments of different orders), and degradation of organic substances to primary mineral products by mineralising micro-organisms. It is the dynamic equilibrium of these processes on a global scale that determines both the very existence of life on Earth during a geologically long period and the chemical composition and the direction of chemical processes taking place in hard rock, water and the atmosphere.

Today total mankind's industrial activity even in peacetime proves to be a sufficiently powerful factor introducing tangible disturbances in the age-old life cycle of the biosphere. This is reflected in the changes in the gaseous composition of the atmosphere, hydrological conditions of natural water, etc. Incomparably bigger changes will inevitably be caused merely by massive release of thermal energy, carbon dioxide, and aerosols as a result of a large-scale nuclear conflict. This particularly applies to the tropical zones which will become extremely vulnerable with a drop in temperature.

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Hundreds of millions of people and large numbers of animals will be killed in war zones in the first few days. Recomposition of their remains will be accompanied by the spread of the products of their decay and putrefaction micro-organisms on an unprecedented scale. An explosive multiplication of some species of insects, including carriers of epidemics, is also predicted. Epidemics that will be caused by mass death of people, lack of medical aid, destruction of water supply systems, etc. will be accompanied by mass outbreaks of diseases caused by the destruction of stockpiles of biological weapons.

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It is hard to predict the specific manner in which economic systems of the developing countries are going to collapse. One thing is clear though: besides the cessation of external economic ties a factor of no small importance would be destruction of life in the cities turning the centers of culture and civilisation into seats of famine, epidemics and, possibly, even chaos.

The 180 million Africans in cities will inevitably fall victims to famine. Both imports and domestic food supplies to cities, particularly in the conditions of "a nuclear winter", would be paralysed. Africa's subsistence or semi-subsistence agriculture, archaic by nature, is not adapted for effective food supply to the cities. Even today food requirements of large sections of urban population are largely met by food imports. For example, in 1980 African states imported 21 million tons of grain from developed countries, chiefly to supply to the urban centers.

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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, 31 January 1985, pp. 23-24, 34-41, 46-50 and 52-55.

"Canada is already accustomed to severe winters. Her plants and animals are very hardy, and her agriculture is fine-tuned to a short growing season. For these reasons it may be argued that a winter attack, arriving while the inland surface is already extensively frozen and snow-covered, would have less impact than one delivered in spring or summer. It might also be assumed that a direct attack on her own surface would be on a small scale by comparison with those delivered to U.S., European and Soviet targets.

The three-dimensional modelling at NCAR reported at the Ottawa Workshop by L. D. Danny Harvey (Harvey and Schneider, unpublished; Covey et al., 1984) confirms "that the large-scale climatic response to a nuclear war depends strongly on the season, and that regional and local responses as well depend strongly on locations and antecedent meteorological conditions". In fact the NCAR work indicates that if smoke of optical depth 3 is uniformly distributed around the northern hemisphere between 30 and 70 deg N. there will be substantial disturbances of the circulation even in the tropics and the southern hemisphere, and in both northern summer and winter. Summer conditions yield the largest disturbance.

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After only two days freezing conditions will have penetrated southward into northern Ontario and Quebec, and along the western Cordillera to the U.S. border. After ten days all of Canada will be much cooled, and deep sub-freezing temperatures will be established from the Great Lakes westward. A similar refrigeration will have affected most of the Soviet Union. An attack in late spring would effectively give Canada a year without a summer.

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The reduction in sunlight, and resulting cold, would kill many species of animals and plants. The severity would depend upon the season in which an attack took place -- plants being most vulnerable in the summer -- but would be castastrophic under any circumstances. Light would be reduced to the level where green plants (those surviving the acute impacts of radiation and cold) were either unable to survive, or were not able effectively to reproduce themselves, or provide harvestable crops. The rate of photosynthesis is almost directly proportional to available sunlight. Plant productivity reaches the compensation point (meaning the threshold in which a plant's metabolism is sufficient only for housekeeping and will not support growth or crop production) when illumination falls to 5-15 per cent of the normal. However, plants cannot grow or survive for long at this level of illumination.

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Despite the problems of prediction it is beyond question that if a nuclear exchange between the superpowers of the northern hemisphere takes place, the Canadian environment -- irrespective of whether or not Canada receives direct hits from nuclear warheads -- will be seriously affected. This might occur at levels of exchange well below those considered by the reference scenarios.

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Agriculture would be even more seriously affected than natural biological systems. Agricultural production is the result of an extremely specialised system in which hybrid cereals (most of which are annuals) are grown under intensive management and require large inputs of energy, fertilizer and pesticides, and have been extended close to their ecological and physiological limits.

Given the marginal nature of Canadian farming and its inherent fragility, it is pertinent to ask what sort of reductions in sunlight and temperature would be required to affect agriculture adversely, and how such reductions relate to the predictions of the nuclear winter scenarios.

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A further consequence of such temperature changes would be the elimination of corn (maize) from Canada, and the northern tier of the U.S.A. (Stewart, personal communication) pending the development of new varieties with a much greater tolerance to cold.

It is important to note that these data refer to maturing wheat. Cereal crop plants need to do more than survive, they need to reproduce. Inability to produce flowers and seeds is equivalent to destruction. For example, a fall in temperature that would reduce <u>total</u> plant growth by only a small amount could prevent seed maturation. Simply, it might be possible to grow wheat and barley that do not produce ears, or corn plants that do not set cobs. Of even more significance than changes in average temperature is the number of frost-free days in the summer. An early fall, or late spring, could completely eliminate a year's crop.

A reduction in sunlight would cause a commensurate drop in the rate of photosynthesis, affecting both growth and production. H. D. Grover ..., reminds us that, in addition to its direct role in driving photosynthesis, sunlight is also important in a variety of other physiological activities such as dormancy, flower development, fruit maturation, shoot development, directional growth, leaf fall and the development of frost hardiness. Interference with these activities could have profound and negative consequences for both crops and the natural vegetation, and will compound the effects of the cooling.

Other effects, for example a decrease in precipitation following the development of a stable atmosphere, might similarly be expected to have a negative impact on production. The social disruption (considered elsewhere) following the aftermath of the attack would remove the technological base so necessary to support intensive agriculture (for example, fuel, pesticide and fertiliser production, farm machinery, transport systems).

There is some disagreement concerning the relative severity of impacts resulting from attacks taking place in different seasons. One view suggests that a summer attack would be most serious, affecting the plants when in sap and when resistance to cold was lowest, ensuring that there would be no yield, or seed for the following year. The implication is that a winter attack would be less severe because some seeds would then be cold hardened and dormant in the ground. A converse view suggests that the effects of a late summer or winter attack would continue into the spring, preventing germination and ensuring that there would be no crop until at least the second season (assuming seed reserves survived). Either prospect is appalling, and both might occur. The danger would be that agriculture would have to be re-established without the benefit of a breeding stock and wide base of genetic reserve, for it is assumed that much of these will have been consumed and lost. Even if conditions are conducive to agriculture, it will not necessarily be possible to raise the crops previously grown in the region. The survivors may well have to redevelop agricultural technology in order to feed themselves.

Whatever the magnitude and duration of the nuclear winter and its influence upon the growing season and temperature, it is clear that cereal production will be severely threatened, or completely eliminated, if significant cooling occurs.

Current stored food reserves in Europe and North America will suffice for months, but in Africa and Asia stocks are measured in weeks, and sometimes days. Given the reliance of ourselves, and the nations of the southern hemisphere (but also Europe and the Soviet Union), on the agricultural production of North America (the U.S. and Canada are primary exporters of cereals) it is pertinent to consider that, even if the more dire consequences of the nuclear winter scenarios prove to have been exaggerations, the intensive agriculture on which our society relies could be eliminated in the aftermath of a nuclear strike of quite modest size. The anthropologist Wenke reminds us that

> the correspondence between agriculture and the town, cities, and other cultural elaborations we call civilisation is absolute. ... The critical advantage of modern industrial peoples over hunters and gatherers ... food production: if for some reason, the world's present population were required to assume our ancestors' reliance on undomesticated plants and animals, most of us would surely starve.

These issues have not been studied in the specific context of a nuclear winter, and much of what has been said is speculative; but the relationship between temperature and cereal production, between illumination and photosynthesis, for example, are well understood by plant biologists and the implications drawn from these assessments are probably robust. The magnitude and duration of the temperature depressions proposed by the reference scenarios of the nuclear winter seem <u>prima facie</u> to be sufficient to give cause for concern about the ability of Canadian agriculture to survive even a small nuclear strike.

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Freshwater in the northern hemisphere would probably be covered by ice to a depth of 1-1.5 m resulting in the widespread death of natural plant and animal populations, and the disruption of social services. Surface water and ultimately ground water would be polluted by radioactive substances, pyrotoxins, soot and dust, and silting from the extensive soil erosion.

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Basic principles suggest that adverse impacts would be less among those species that reproduce rapidly (e.g., rats) or have greater resistance to radiation (e.g., insects, which are ten or more times more resistant to ionising radiation than either coniferous trees or humans). They would suddenly find themselves rich in resources and lacking competition. In short, pests would flourish at the expense of those plants and animals on which our society depends.

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The seas would probably not suffer much physical change -- the large volume of the oceans, and their heat capacity, making them resistant to temperature fluctuations. The reduction of sunlight (by the smoke/dust pall) and possibly the increase in UV radiation (caused by the diminution of the ozone layer) could reduce the productivity of the microscopic plants (phytoplankton) of the surface layers, on which all life in the oceans ultimately depends. Perhaps only a few days of darkness would be sufficient to kill the phytoplankton, or render them dormant. A widespread loss of fisheries, and of non-commercial species, within two to six months has been postulated (see Ehrlich et al., 1983, 1984).

The coastal, estuarine and continental shelf environments, those areas which support most commercial fisheries, would be especially vulnerable to pollution from the land caused by soil erosion and carriage of pollutants by rivers. The biota would be exposed to suspended, toxic particulates which would have a detrimental effect, especially upon microphagous filter feeders. These impacts are plausible but have not yet received detailed appraisal by biological oceanographers, or experts in marine systems ecology.

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The tropical areas of the northern hemisphere would be extensively affected, those of the southern hemisphere probably less so. Few sub-tropical and tropical plants have dormant phases in their life cycles that would confer seasonal protection against the cold. The biological productivity of many tropical plants is only slightly above the compensation point, leaving little margin for survival should temperature and sunlight drop below a critical threshold. The tropical rainforests are notoriously fragile -- any appreciable destruction leading to severe erosion of soils, and perturbations of the hydrological and biogeochemical cycles. Cooling during the Pleistocene period, and direct evidence from the Friagem effect (when polar air masses occasionally reach the edge of the Amazonian rain forest, with catastrophic results) provide a persuasive case for regarding the tropical forests as being at risk. Conversely, a nuclear winter may have a less serious effect upon the tropical deserts.

Finally, it should be noted that the tropics are a major reserve of genetic diversity, a resource that will be particularly at risk. The principal cultigens of North America, those that formed the basis of the earliest horticulture and agriculture of the native peoples, and which are still of great economic importance (e.g., maize, squash, potatoes) are introductions from tropical and subtropical latitudes. Because of our reliance on monocultural varieties, there is already concern among agriculturalists about the loss of genetic diversity. In the period following nuclear winter, when there may be a need to develop rapidly new, adaptive varieties, the loss of genetic stock from the low latitudes might be a major constraint to the re-establishment of food production.

Long-Term Climatic Anomalies

A recurrent theme in our deliberations has been the concern that ecosystems and agriculture can be devastated when the long-term mean temperature changes by only a small amount. For example, the Tambora and Krakatoa eruptions, and the recent El Niño, caused shifts in air temperature in the order of one or two (mean value less than one) degrees Celsius and caused widespread effects. Although there are no precedents for changes such as those proposed by the nuclear winter scenarios which predict large (5-30 degrees C) but transient (weeks to months) depressions of air temperature, it is clear that such perturbations must inevitably shift climatic averages to levels that might have severe consequences for the biota, food production and society.

Long-term (5-10 years) climatic anomalies resulting in shorter growing seasons, more severe temperature fluctuations (hot and cold), and reduced precipitation are probable secondary consequences of the nuclear winter. Agriculture, already suffering from the devastation of the immediate, post-attack period, will therefore be placed in double jeopardy. New varieties will be required to cope with the changed regimen, and it will be difficult to provide these, given the anticipated disruption of the technological infrastructure necessary for research and development. It may not be possible to establish adequate agricultural productivity. Indeed, small climatic perturbations causing irregular late-spring or early-fall frosts, or summer droughts (for example) could prevent any organised, high-intensity agriculture in Canada for as long as a decade.

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Immediate Period (weeks to three months)

The weeks following the onset of the nuclear winter will be characterized by a rapid drop in temperature and darkening of the sky during daylight. Some survivors will suffer the effects of radiation sickness. Electromagnetic pulses will have disabled power utilities and communications systems and social services, already stressed by blast and fire. If the attack occurs in summer, photosynthesis will be diminished, and coupled with the cold there will be widespread death of plants, including crops. The loss of a complete year of agricultural production must be contemplated. The immediate effects of a winter attack will be less severe on the dormant and cold-hardened plants of Canada, but if the coldness and darkness persists to the spring, it is unlikely that perennials will emerge from dormancy, or that annuals will germinate even if they can be planted.

Direct contamination of food and water will be greatest in summer. Following a winter attack, surface and ground waters will receive a pulse of contaminants that have accumulated in the snowpack during the winter and drawing upon what is known from the effects of acid precipitation in eastern Canada, this may be more damaging than the more immediate impacts.

The possibility of intense fire storms injecting particulates into the upper troposphere and contributing to the extinction of solar radiation will not be considered here. It is possible that innumerable forest and brush fires will be ignited, burning at low temperature over a wide area. These fires, fuelled by vegetation killed by radiation, cold and the extinction of light, might burn for weeks. Large amounts of vegetation, and the organic component of the soil could be destroyed, leaving an ash rich in soluble minerals. These minerals could be irreversibly leached, leading to impoverished soils, and polluted ground waters, reservoirs, lakes, rivers, and streams.

The influx of pollutants (radionuclides, soot, pyrotoxins and excess sediment and nutrients) to rivers and streams could pollute estuaries and the inshore regions which support the most productive fisheries. These negative impacts might be augmented by increased coastal storms and the impairment of photosynthesis and primary production in marine food chains.

Initially, the population will have to live on locally stored and directly accessible food, medicines and energy reserves. Following a winter attack, society might continue to function with some degree of order for a short period, until reserves, particularly of imported commodities including liquid fuels, are diminished.

Intermediate Period (a few months to two years)

The atmosphere will probably return to normal during this period. Recovery of changes in the lithosphere (eroding soils, disturbed drainage, chemical imbalances) will probably take much longer, and the biosphere will be drastically and perhaps permanently altered.

Canada will be faced with the need to achieve a sustainable balance between the demands of the population and the resources (primarily food and energy) that can be obtained locally and regionally, or by importation. So to the administrative and social infrastructure, there will be a need to re-establish a health-care system. This possibility is predicated upon the establishment of some form of governmental control and social order.

It may be argued that Canada has regions in which, given a reasonable environment and potential for biological productivity, modest numbers of people are able to flourish in a self-sufficient manner -- it is the history of the country, and some of the skills remain. But even given a return to pre-war environment and productivity, it is unlikely that twenty-six million mostly urbanised Canadians, or even half that number, would achieve self-sufficiency. Moreover, the availability of food will depend upon the seed stocks that have survived fire and radiation, and the biological productivity to the land in the first two years following the attack.

Self-sufficient living will depend on the availability of arable land, soils, forests and the survival of seeds and seed plants, all of which will be influenced by the season of attack. Other natural phenomena will also be important. For example, migratory birds will be vulnerable to the effects of the nuclear winter, whereas the insects on which they feed will flourish, being relatively unaffected by the cold, and having a large tolerance to radiation. The emergent agriculture may then be faced with pestilence at a time when industry cannot supply pesticides, and the natural predators on insects are in decline.

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The surviving population will be affected by the residual effects of radiation. One of these is likely to be an increased susceptibility to disease to which the problems of malnutrition (perhaps widespread starvation), debilitation of general health (resulting from poor housing and waste treatment), poor water quality, and the inadequacy of health care will have to be added. The control of communicable disease; the need to maintain order; and widespread starvation, or at best malnutrition: all will confront a residual society.

Long-Term Period (two years to two decades)

During this period, the planetary and regional ecosystems are either re-established or attain a new norm.

The severity of the long-term impact will depend upon the nature and persistence of the cloud of smoke and dust. If it spreads to the southern hemisphere, and reduces solar illumination to one-tenth or less of the norm, and persists long enough to affect the growing seasons of both hemispheres, the consequences will be severe and inevitable. The destruction of terrestrial and aquatic (marine and freshwater) vegetation will disrupt the food chains, and cause the death of many species of animals. There is almost no precedent for examining these consequences save from paleontology, which suggests that the former ecological structure will not be re-established. The catastrophic extinctions of the past reassure us that life has never been wholly extinguished, but the evidence suggests that the old order does not return. It is the larger, specialised, and dominant organisms that die out. If

- the attack takes place during a normal period of biological dormancy (such as the Canadian winter),

- the dust cloud is thin, restricted and patchy (so that illumination levels are not drastically reduced and sunlight is able to penetrate sporadically), and

- there has not been widespread destruction of forests and arable lands by fire,

regional ecosystems might survive and relatively intact areas could serve as reserves of biological diversity from which regions may be reinvaded, either naturally, or as part of a management system. It should be borne in mind that in this process pests would have the advantage over useful species: more likely Jonathan Schell's "A Republic of Insects and Grass" than a Dominion of Beef and Barley.

Presumably, after something like five years, a balance will have been established between the human population and food supply, diseases will have run their course and taken their toll, and pests will have been controlled (or at least agriculture and medicine will have adapted to them). During the following years, human skills and energy, acting in concert with the recovery of natural systems and agriculture, will make possible the rebuilding of an economically productive planet.

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From: The Potential Effects of Nuclear War on the Climate, a report of the Secretary of Defense to the United States Congress, United States of America, March 1985.

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

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From: "Global consequences of a nuclear war: a review of recent Soviet studies", by A. S. Ginsburg, G. S. Golitsyn and A. A. Vasiliev, of the Academy of Sciences of the USSR, in World Armaments and Disarmament, SIPRI Yearbook 1985, chap. 4, pp. 109-111 and 116-117.

"Izrael describes the main large-scale consequences of a nuclear war and their influence on ecological systems. 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.

It is furthermore noted by Izrael that surface explosions would send up to 5,000 tonnes of rock per kiloton of nuclear explosion power into the atmosphere, of which about 1,000 tonnes would be made up of particles up to 3 um in size. The average size of aerosol particles formed by explosions in air is a fraction of a micrometre.

The joint effect of the injection into the atmosphere of nitric oxides and aerosol is examined at some length by Obukhov and Golitsyn. Described in particular is the effect observed in 1978 by a Soviet cosmonaut, G. M. Grechko: while on board an orbital station, Grechko noticed blue stripes above the horizon, inside which could be seen thin layers of a lighter shade. Calculations carried out in the Institute of the Physics of the Earth's Atmosphere of the Soviet Academy of Sciences showed that the stripes are formed by light passing through these layers and that the emergence of the lighter-coloured interval is due to the reduced concentration of ozone at these altitudes because of its destruction by aerosol particles.

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In 1983 Soviet scientists published a number of papers devoted to the elaboration of the nuclear winter hypothesis -- that is, of a strong drop in the temperature of the Earth's surface caused by the global spreading in the atmosphere of tiny particles of smoke from mass fires of a nuclear explosion.

According to these studies one can assume that a nuclear winter would result from the following sequence of basic physical processes in the climatic system. In normal circumstances the energy radiated by the Sun is absorbed by the land surface, by the ocean, and to a lesser extent by the atmosphere. The radiation of the Sun warms them up non-homogeneously in different latitudes and in different seasons of the year. Uneven heating sets the atmosphere and ocean layers into motion and is responsible for the climate to which ecological communities and man have adjusted. Natural and anthropogenic changes (due to the development of the world economy) in climate occur rather slowly -- in the course of several decades or more. But in a global catastrophe such as a nuclear war the alteration of the atmosphere and surface of the Earth would occur much more rapidly.

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The main ideas regarding nuclear night or nuclear winter were developed during 1983. Research proceeded in different directions: analysis of ecological and economic consequences of nuclear winter; and more precise definition of physical processes which occur in the atmosphere and on the surface of the Earth because of multiple nuclear explosions and resulting fires. The report of the

Committee of Soviet Scientists Against Nuclear War, called 'Global consequences of nuclear war and developing countries', is an example of research in the first direction. The report states that although modern science is incapable of making an evaluation of all the fatal consequences of nuclear winter and other aspects of nuclear war for the ecological systems, agriculture and economies of tropical zones, what is already known is enough to conclude that tropical agriculture in Africa and in most tropical countries of Asia and Latin America would cease to exist. Tropical crops will not only be destroyed as a result of the cold and darkness but will also not be revived because of the termination of deliveries of insecticides, other pesticides and chemical fertilizers from the developed countries. Tropical forests, which are one of the main sources of oxygen and a sustainer of organic life on Earth, will be destroyed by even a short period of darkness and cold because they can survive only within a narrow climatic range and cannot endure dramatic fluctuations of the temperature and light levels. Nuclear war would doom the majority of the population in the developing countries to cold, hunger, illnesses and in the long run to possible extinction.

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From: <u>The Threat of Nuclear War: A New Zealand Perspective</u>, The Royal Society of New Zealand, 1985, pp. 12 and 14-15.

"The spread of the nuclear clouds from the middle latitudes of the northern hemisphere depends on the global wind systems and the heights in the atmosphere to which the debris is injected. The detonation of a 1 Mt warhead in the lower atmosphere can put debris to a height of about 20 km. The material at this height is in the stratosphere above the levels at which most rainfall is formed. The diffusing cloud travels with the global wind systems and remains in the atmosphere for months to years before being brought to the ground. Because there is an exchange of air across the equator, the cloud would spread from northern latitudes into the southern hemisphere. After the El Chichon volcanic eruption in Mexico in 1982, satellite observations showed a thin veil of volcanic dust in the stratosphere covering most of the globe within a year.

The explosion clouds from lower yield weapons will remain in the lower atmosphere (the troposphere) and will normally have the much shorter residence time of days to weeks. A lot of the debris will be deposited in rain within a few days and the rest diffused by the turbulent motions of the atmosphere and deposited later.

...

There is, however, an imperfect knowledge of the behaviour of the debris in the atmosphere, and our ability to model atmospheric motions which determine the subsequent distribution and effects of the debris is limited. The simplifications that have to be introduced into the calculations make accurate forecasts of the long-term effects of nuclear war impossible at present. Further uncertainties are introduced because assumptions necessarily have to be made about the extent, location, and time of year of a nuclear war.

Earlier experiments had suggested that the long-term effects on the southern hemisphere of a nuclear war confined to the northern hemisphere would be slight. Recent work has shown that this is probably not true.

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Outlook for the southern hemisphere

Approximations were made at each stage of the complex calculations and important atmospheric processes had to be left out. The results must therefore be considered as qualitative and not as precise quantitive forecasts.

However, they have been confirmed by another more recent computer simulation carried out by a group at the National Center for Atmospheric Research (NCAR) in the United States. This atmospheric model is much more realistic than that used by Turco and his colleagues. It was used to calculate the atmospheric consequences over a few weeks of the smoke generated by a nuclear war in the middle latitudes of the northern hemisphere. The smoke was assumed to be evenly spread between latitudes 30°N and 70°N. It caused almost complete blocking of the incoming sunlight.

It was found that middle latitude surface temperatures in the interiors of the continents dropped below freezing in a matter of days regardless of the season. Changes brought about in the large-scale circulation of the atmosphere were able to spread the aerosols well beyond the regions in which the smoke was originally generated. A greatly enhanced cross-equator flow was found, especially in the northern hemisphere spring. This changes the expectation of relative southern hemisphere immunity from a northern war.

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From: "The Environmental Consequences of Nuclear War", report of the Steering Committee for ICSU/SCOPE, September 1985.

"... Many conclusions are evident from considering these vulnerabilities to nuclear war perturbations. These include:

Natural ecosystems are vulnerable to extreme climatic disturbances, with differential vulnerability depending on the ecosystems type, location, and season of effects. Temperature effects would be dominant for terrestrial ecosystems in the Northern Hemisphere and in the tropics and sub-tropics; light reductions would be most important for oceanic ecosystems; precipitation effects would be more important to grasslands and many Southern Hemisphere ecosystems.

The potential for synergistic responses and propagation of effects through ecosystems implies much greater impacts than can be understood by addressing perturbations in isolation. For example, increased exposure to UV-B and to mixtures of air pollutants and radiation, while not crucially harmful for any one stress, might collectively be very detrimental or lethal to sensitive systems because of synergistic interactions.

Fires as a direct consequence of a major nuclear exchange could consume large areas of natural ecosystems, but fire-vulnerable ecosystems are generally adapted to survive or regenerate via a post-fire succession. Other direct effects of nuclear detonations on ecological systems would be limited in extent or effect.

The recovery of natural ecosystems from the climatic stresses postulated for an acute phase following a major nuclear war would depend on normal adaptations to disturbance, such as through presence of pores, seed banks, seedling banks, vegetative growth, and coppicing. For some systems, the initial damage could be very great and recovery very slow, with full recovery to the pre-disturbed state being unlikely. Human-ecosystem interactions could act to retard ecological recovery.

Because of limitations in the amounts of utilizable energy, natural ecosystems cannot replace agricultural systems in supporting the majority of humans on Earth, even if those natural ecosystems were not to suffer any impacts from nuclear war.

Consequently, human populations are highly vulnerable to disruptions in agricultural systems.

Agricultural systems are very sensitive to climatic and societal disturbances occurring on regional to global scales, with reductions in or even total loss of crop yields possible in response to many of the potential stresses. These conclusions consistently follow from a suite of approaches to evaluating vulnerabilities, including historical precedents, statistical analyses, physiological and mechanistic relationships, simulation modelling, and reliance on expert judgement.

The vulnerabilities of agricultural productivity to climatic perturbations are a function of a number of different factors, any one of which could be limiting. These factors include: insufficient integrated thermal time for crops over the growing season; shortening of the growing season by reduction in a frost-free period in response to average temperature reductions; increasing of the time required for crop maturation in response to reduced temperatures; the combination of the latter two factors to result in insufficient time for crops to mature prior to onset of killing cold temperatures; insufficient integrated time of sunlight over the growing season for crop maturation; insufficient precipitation for crop yields to remain at high levels; and the occurrence of brief episodic events of chilling or freezing temperatures at critical times during the growing season.

Potential disruptions in agricultural productivity and/or in exchange of food across national boundaries in the aftermath of a large-scale nuclear war are factors to which the human population is highly vulnerable. Vulnerability is manifested in the quantities and duration of food stores existing at any point in time, such that loss of the continued agricultural productivity or imports that maintain food levels would lead to depletion of food stores for much of the world's human population in a time period before it is likely that agricultural productivity could be resumed.

Under such a situation, the majority of the world's population is at risk of starvation in the aftermath of a nuclear war. Risk is therefore exported from combatant countries to non-combatant countries, especially those dependent on others for food and energy subsidies and those whose food stores are small relative to the population.

The high sensitivity of agricultural systems to even relatively small alterations in climatic conditions indicates that many of the unresolved issues among the physical scientists are less important, since even their lower estimates of many effects could be devastating to agricultural production and thereby to human populations on regional or wider scales.

Longer-term climatic disturbances, if they were to occur, would be at least as important to human survival as the acute, early extremes of temperature and light reductions, suggesting that much greater attention should be given to those issues. Similarly, much greater attention is needed to resolve uncertainties in precipitation reduction estimates, since many of the agricultural systems are water-limited, and reduced precipitation can significantly reduce total production.

Factors related to the possibility and rates of redevelopment of an agricultural base for the human population would have much influence on the long-term consequences to the human population. Interactions with societal factors would be very important.

Global fallout is not likely to result in major ecological, agricultural, or human effects, as compared to effects of other global disturbances. Local fallout, on the other hand, could be highly cnsequential to natural and agricultural systems and to humans; however, the extent of coverage of lethal levels of local fallout and the levels of internal doses to humans from such fallout are inadequately characterized.

Human populations are highly vulnerable to possible societal disruptions within combatant and non-combatant countries after a large-scale nuclear war, such as in the consequent problems of distribution of food and other limited resources among the immediate survivors. This is an area requiring a level of serious scientific investigation that has not yet been brought to bear on these issues."

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VIII. CONCLUSIONS OF VARIOUS STUDIES

From: "The Atmosphere after Nuclear War: Twilight at Noon" by Paul Crutzen and John W. Birks, in Ambio, the journal of the Royal Swedish Academy of Sciences, vol. 11, No. 2-3, 1982, pp. 123-124.

"Conclusions

In this study we have shown that the atmosphere would most likely be highly perturbed by a nuclear war. We especially draw attention to the effects of the large quantities of highly sunlight-absorbing, dark particulate matter which would be produced and spread in the troposphere by the many fires that would start burning in urban and industrial areas, oil and gas producing fields, agricultural

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lands, and forests. For extended periods of time, maybe months, such fires would strongly restrict the penetration of sunlight to the earth's surface and change the physical properties of the earth's atmosphere. The marine ecosystems are probably particularly sensitive to prolonged periods of darkness. Under such conditions it is likely that agricultural production in the Northern Hemisphere would be almost totally eliminated, so that no food would be available for the survivors of the initial effects of the war. It is also quite possible that severe, worldwide photochemical smog conditions would develop with high levels of tropospheric ozone that would likewise interfere severely with plant productivity. Survival becomes even more difficult if stratospheric ozone depletion also takes place. It is therefore, difficult to see how much more than a small fraction of the initial survivors of a nuclear war in the Northern Hemisphere could escape famine and disease during the following year.

In this paper we have attempted to identify the most important changes that would occur in the atmosphere as a result of a nuclear war. The atmospheric effects that we have identified are quite complex and difficult to model. It is hoped, however, that this study will provide an introduction to a more thorough analysis of this important problem."

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From: "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions", by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and C. Sagan, in Science, vol. 222 (28 December 1983), p. 1290. Copyright 1983 by the American Association for the Advancement of Science.

"Discussion and Conclusions

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

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

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

trigger severe aftereffects. It is much less likely that a 5000- to 10,000-MT exchange would have only minor effects.

3) The climatic impact of sooty smoke from nuclear fires ignited by airbursts is expected to be more important than that of dust raised by surface bursts (when both effects occur). Smoke absorbs sunlight efficiently, whereas soil dust is generally nonabsorbing. Smoke particles are extremely small (typically less than 1 um in radius), which lengthens their atmospheric residence time. There is also a high probability that nuclear explosions over cities, forests, and grasslands will ignite widespread fires, even in attacks limited to missile silos and other strategic military targets.

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

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

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

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

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

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From: "Long-Term Biological Consequences of Nuclear War" by Paul R. Ehrlich et al., in Science, vol. 222 (23 December 1983), p. 1299.

"Conclusions

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

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

It seems unlikely, however, that even in these circumstances Homo sapiens would be forced to extinction immediately. Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects alone resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of over 1 billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere. Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future. In any large-scale nuclear exchange between the superpowers, global environmental changes sufficient to cause the extinction of a major fraction of the plant and animal species on the Earth are likely. In that event, the possibility of the extinction of Homo sapiens cannot be excluded."

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From: The Effects on the Atmosphere of a Major Nuclear Exchange, report of the Committee on the Atmospheric Effects of Nuclear Explosions, National Research Council, National Academy of Sciences, Washington, D.C., 1985, pp. 6-9.

"Conclusions

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

Nevertheless, the committee finds that, unless one or more of the effects lie near the less severe end of their uncertainty ranges, or unless some mitigating effect has been overlooked, there is a clear temperate zone (and, perhaps, a larger segment of the planet) that could be severely affected. Possible impacts include major temperature reductions (particularly for an exchange that occurs in the summer) lasting for weeks, with subnormal, temperatures persisting for months. The impact of these temperature reductions and associated meteorological changes on the surviving population, and on the biosphere that supports the survivors, could be severe, and deserves careful independent study.

A more definitive statement can be made only when many of the uncertainties have been narrowed, when the smaller scale phenomena are better understood, and when atmospheric response models have been constructed and have acquired credibility for the parameter ranges of this phenomenology.

The committee also draws several more specific conclusions:

1. In an extensive nuclear exchange, explosions over urban areas and forests would ignite many large fires. Massive smoke emissions are an important aspect of nuclear warfare that have only recently been recognized. For the major 6,500-Mt nuclear war considered here, fires could release massive amounts of smoke into the troposphere over a period of a few days. Much of the smoke might be removed by meteorological processes within several weeks, depending on feedback effects, but significant amounts could remain for several months. During its tenure in the atmosphere the smoke would gradually spread and become more uniformly distributed over much of the northern hemisphere, although some patchiness would be likely to persist. Light levels could be reduced by a factor of 100 in regions that were covered with the initial hemispheric average smoke load, causing intense cooling beneath the particulate layer and unusually intense heating of the upper layer. While large uncertainties currently attend the estimates of smoke emissions, and of their optical and physical consequences, the baseline case implies severe atmospheric consequences.

2. The production of smoke from fires, and the implied effects on the atmosphere, is more directly linked to the extent of detonation over urban areas than to the aggregate yield of a nuclear exchange. The industrialized nations of the world have concentrated a large proportion of their resources and combustible fuels in the vicinity of the central areas of their large cities. Any war scenario that subjects these city centers to nuclear attack, even one employing a very small fraction of the existing nuclear arsenal, could generate nearly as much smoke as in the 6,500-Mt baseline war scenario.

3. The climatic impact of soot is very sensitive to its lifetime in the perturbed atmosphere and the uniformity of its distribution. The lifetime of soot is highly uncertain, particularly in the upper troposphere. The perturbation itself would produce severe new effects, many of which could tend to increase the residence time of the soot. Although the lofted soot (and dust) would rapidly

spread around the latitude band of injection, the distribution could be uneven for several months, with continent-size patches of lesser and greater density, particularly near the southern edge of the affected zones.

4. In the baseline nuclear war scenario, hundreds of teragrams of dust would be injected into the atmosphere from surface detonations. A significant fraction of the dust consisting of particles with radii less than one micron (1um) would be expected to remain aloft for months. About one-half of these submicron particles would be injected into the stratosphere and would produce some long-term reduction of sunlight at the earth's surface, even after smoke and dust at lower altitudes were removed. This stratospheric dust alone would lead to perceptible reductions in average light intensities, and continental surface temperatures would fall measurably. In a plausible scenario that involves more groundburst attacks against very hard targets than are assumed in the baseline case, the possible dust effects are several times larger.

5. It is not possible at this time to estimate the most probable average temperature changes at the surface caused by smoke and dust lofted in the baseline case; nor would such a single value, even if available, meaningfully describe the situation. In addition to the large uncertainties in many of the critical physical parameters and the inherent limitations of the models available for computer simulations, the available calculations reflect wide seasonal and geographical differences. Recent general circulation model simulations that incorporate simplifying assumptions indicate that a baseline attack during the summer might decrease mean continental temperatures in the northern temperate zone by as much as 10° to 25°C, with temperatures along the coasts of the continents decreasing by much smaller amounts. In contrast, an attack of the same size during the winter, according to these simulations, might produce little change in temperature in the northern temperate zone, although there could be a significant drop in temperatures at more southern latitudes.

6. The nitrogen oxides deposited in the stratosphere by nuclear detonations would reduce the abundance of ozone. For the 6,500-Mt nuclear war, the northern hemisphere ozone reduction could become substantial several months after the war. Estimates based on current stratospheric structure suggest that the amount of ozone reduction would decrease by one-half after about 2 years. At the time of maximum ozone reduction, the biologically effective ultraviolet intensity (using the DNA action spectrum) at the ground would be approximately one and one-half times the normal levels. Initially, the presence of dust and smoke particles in the atmosphere would provide a measure of protection at the surface from the enhanced ultraviolet radiation. This protection would gradually diminish as the particles were removed.

7. This study has concentrated on the possible effects that a nuclear war could have on the northern hemisphere, primarily within the mid-latitude region (30°N to 70°N) where the nuclear exchange would be concentrated. Although southern hemisphere effects would be much less extensive, significant amounts of dust and smoke could drift to and across the equator as early as a few weeks after a nuclear exchange. A large rate of transport across the equator driven by heating in the debris cloud cannot be ruled out. Indeed, such heating-enhanced cross-equatorial circulation has been found for spring and summer months in computer simulations.

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8. Some prehistoric volcanic eruptions and impacts from extraterrestrial bodies have released energies corresponding to levels that would be released in a major nuclear exchange and may have lofted massive amounts of dust; however, neither type of event provides a useful direct analog to the nuclear case because neither type involved the production of highly absorbing soot particles. Furthermore, the atmospheric consequences of prehistoric natural events of these proportions are not known, and their effects on the fossil record, if any, have not been sought in any systematic way. Accordingly, available knowledge about prehistoric volcanic and impact events provides neither support nor refutation of the committee's conclusions.

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

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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, January 1985, pp. 63-69.

"SUMMARY AND CONCLUSIONS

The Committee finds that

1. A nuclear winter in the wake of a major nuclear exchange appears to be a formidable threat. If calculations are correct -- and the Committee believes them credible -- temperatures in the interior of continents will plunge by many degrees shortly after the exchange, probably far below freezing in many mid-latitude areas. Severe damage or destruction will ensue for crops and vegetation. The winter will last for some weeks to several months, and will have lasting repercussions.

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The Models

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

9. 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;

10. 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;

11. 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.

Climatic Impact

12. Although the main impact on climate would be manifest in three latitudes where the major nuclear exchange took place -- presumably northern mid-latitudes -- there would be substantial cooling and disturbance of the circulation in tropical latitudes and the southern hemisphere, and long-term climatic perturbations are possible;

13. To clarify the nuclear winter hypothesis, it is important that the impact of nitric oxide (formed in nuclear fireballs) on ozone levels be examined further. It has been widely assumed that decreases in ozone caused by nitric oxide produced in this manner would lead to ozone dissociation, and hence increased levels of damaging ultraviolet radiation at the earth's surface. This may be so, but other circumstances must now be taken into account. Related processes may result in substantial generation of ozone in the troposphere. The altered thermal structure of the upper troposphere and lower stratosphere implies a possible radical change in the chemistry and dynamics of the ozone layer.

Biological Impact, including that on Agriculture and Fisheries

The Committee agrees with numerous spokesmen that the nuclear winter hypothesis implies severe threats to living communities, and thereby to the security of the human species. There may possibly be extinctions on a scale comparable with known events caused in the past by meteorite or asteroid impacts. But work on the biological impact is less advanced than that on physical events. Tentatively the Committee concludes that, in the case of a major nuclear exchange,

14. Canadian agriculture would be severely affected even if there were only small reductions in growing season temperature, and reductions in sunlight;

15. The degree of damage would depend to a great extent upon the season of attack. Damage might be extremely severe if it affected the early growing season, or destroyed seeds and rootstocks in late summer and fall;

16. Prairie agriculture would be severely affected by even small counterforce strikes, because the main U.S. missile sites are close at hand;

17. Canadian forests are vulnerable to radiation damage from fallout. They might also suffer blow-down by blast from nearby detonations;

18. The forests might suffer extensive fire damage. A 50 megatonne detonation over forests might destroy from 13,000 to 500,000 square kilometres, depending on place and season;

19. All the above stresses would likely encourage pests and weeds at the expense of useful species, so the regrown ecosystems would be inferior in quality for many years and perhaps generations;

20. There will be damage to ocean ecosystems, and hence to fisheries. A few days of darkness could kill much of the phytoplankton, the green plants at the base of the food system. Increased ultraviolet when the sun returns would also damage phytoplankton. A widespread loss of fisheries and of non-commercial fish within two to six months has been inferred;

21. The long-term rebuilding of agriculture and fisheries, once normal climate had returned, would be difficult because of our heavy dependence on technology, seed banks, fertilizers and other aids likely to be in short supply;

22. It is possible that long-term climatic anomalies caused by a nuclear war might hinder or prevent the re-establishment of pre-war (or indeed any) high-intensity agriculture in Canada.

Impact on Society

The Committee was not explicitly asked to consider the social impact of the nuclear winter, nor did its composition allow it to do so in an expert fashion. Nevertheless it tried to visualize what might happen. Clearly the answer for Canada will depend on at least these unknowns:

- the size and nature of the nuclear exchange
- whether Canada will be a target, and if so in what regions
- the extent of physical damage
- the impact on other countries, especially the U.S.A.
- the degree of conflict or cooperation between urban and rural parts of the nation
- the state of preparedness (food storage, security of energy supply, hardening of communications against electromagnetic pulse, etc.)

In the light of these considerations the Committee came to no firm conclusions about the impact on society, but includes in the Supplement speculations on short, intermediate and long-term adaptations to the new, forbidding environment. One conclusion is that

23. The socioeconomic consequences of the various scenarios should be examined in much greater detail by a qualified group of social scientists."

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From: The Potential Effects of Nuclear War on the Climate, Report of the United States Secretary of Defense to the United States Congress, United States of America, March 1985, p. 9.

"Summary Observations on the Current Appreciation of the Technical Issues

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

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

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

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

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

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

..."

* * *

From: "Global consequences of a nuclear war: a review of recent Soviet studies", by A. S. Ginsburg, G. S. Golitsyn and A. A. Vasiliev, in World Armaments and Disarmament, SIPRI Yearbook 1985, pp. 120-121.

"Conclusion

"This review of Soviet research on the global consequences of nuclear war shows that most of this activity was undertaken in recent years. Results essential to explaining the role of those physical processes of the Earth's climatic system that cause nuclear winter were obtained. Corroborative assessments of Earth surface cooling, as a result of the atmosphere filling with the burning products of 'nuclear firestorms', were based on climatic models greatly differing in various complex details.

All the main aspects of the climatic consequences of nuclear war have been analysed in detail, that is: what would burn and where; how much smoke would form; the height and distance it would spread; the time it would remain in the atmosphere; how the atmosphere would heat and the Earth's surface would cool; what changes it would cause in precipitation and in the general circulation and which feedbacks would start working in this complex system.

Quantitative estimates may be given for some of these questions. Others can be analysed only qualitatively. On the whole the problem is so complicated -- and the possibility of climatic catastrophe due to nuclear war is so real -- that co-ordinated international efforts are needed to carry out further systematic research.

Both Soviet and foreign scientists have concluded that the effects of nuclear war would reach the most remote areas of the world. Thus it is clear that ideas of using nuclear weapons even in regional and local crisis situations and equipping 'rapid deployment forces' with nuclear ammunition represent a threat to all mankind. By revealing the climatic consequences of nuclear conflict, scientists from different countries have shown the inconsistency of the concept, still held in some circles, that it is possible to 'wait out' a nuclear war, far from its core. Today it is becoming more and more evident: 'Should nuclear fire start, it will spare no one'."

* * *

From: The Foreword to the ICSU/SCOPE report entitled "The Environmental Consequences of Nuclear War", prepared by the Steering Committee, September 1985.

"Although uncertainties associated with knowledge of physical and biological processes could be substantially reduced by further research, some of these uncertainties are bound to remain large for many years, as explained in the report.

The report does not attempt to provide a single estimate of the likely consequences for humans and their societies of the physical and biological changes projected to be possible after a nuclear war. One reason is that the combinations of possible environmental perturbations are so large and the varieties of environmental and human systems are so numerous and complex that it would be an impossible task to look with detail into all of the ways in which those perturbations might result in an impact. Further, the environmental disruptions and dislocations from nuclear war would be of a magnitude for which there is no precedent. Our present interdependent, highly organized world has never experienced anything approaching the annihilation of people, structures, resources, and disruption of communications that would accompany a major exchange, even if severe climatic and environmental disturbances were not to follow it. The latter could aggravate the consequences profoundly. How the environmental perturbations which would occur at unprecedented scales and intensities would affect the functioning of human society is a highly uncertain subject requiring concerted research and evaluation. Nevertheless, whatever the uncertainties, there can be no doubt that there is a considerable probability a major nuclear war could gravely disrupt the global environment and world society. All possible effects do not have the same probability of occurrence. Sharpening these probabilities is a matter for a continuing research agenda.

The bases for these statements are to be found in the report, along with references to supporting or relevant information. From them we draw the following general conclusions:

(1) Multiple nuclear detonations would result in considerable direct physical effects from blast, thermal radiation, and local fallout. The latter would be particularly important if substantial numbers of surface bursts were to occur since lethal levels of radiation from local fallout would extend hundreds of kilometers downwind of detonations.

(2) There is substantial reason to believe that a nuclear war could lead to large-scale climatic perturbations involving drastic reductions in light levels and temperatures over large regions within days and changes in precipitation patterns for periods of days, weeks, months, or longer. Episodes of short term, sharply depressed temperatures could also produce serious impacts -- particularly if they occur during critical periods within the growing season. There is no reason to assert confidently that there would be no effects of this character and, despite uncertainties in our understanding, it would be a grave error to ignore these potential environmental effects. Any consideration of a post-nuclear-war world would have to consider the consequences of the totality of physical effects. The biological effects then follow.

(3) The systems that currently support the vast majority of humans on Earth (specifically, agricultural production and distribution systems) are exceedingly vulnerable to the types of perturbations associated with climatic effects and societal disruptions. Should those systems be disrupted on a regional or global scale, large numbers of human fatalities associated with insufficient food supplies would be inevitable. Damage to the food distribution and agricultural infrastructure alone (i.e., without any climatic perturbations) would put a large portion of the Earth's population in jeopardy of a drastic reduction in food availability.

(4) Other indirect effects from nuclear war could individually and in combination be serious. These include disruptions of communications, power distribution, and societal systems on an unprecedented scale. In addition, potential physical effects include reduction in stratospheric ozone and, after any smoke had cleared, associated enhancement of ultraviolet radiation; significant global-scale radioactive fallout; and localized areas of heavy toxic air and pollution.

(5) Therefore, the indirect effects on populations of a large-scale nuclear war, particularly the climatic effects caused by smoke, could be potentially more consequential globally than the direct effects, and the risks of unprecedented consequences are great for non-combatant and combatant countries alike.

A new perspective on the possible consequences of nuclear war that takes into account these findings is clearly indicated. In these circumstances, it would be prudent for the world scientific community to continue research on the entire range of possible effects, with close interaction between biologists and physical scientists. It would be appropriate for an international group of scientists to reappraise those findings periodically and to report its appraisal to governments and citizen groups. Increased attention is urgently required to develop a better understanding of potential societal responses to nuclear war in order to frame new global perspectives on the large-scale, environmental consequences. This task is a special challenge to social scientists.

In arriving at these conclusions, we have been moderate in several respects. We have tried to state and examine all challenges to theories about environmental effects of nuclear war, to minimize speculative positions and to factor valid criticisms into discussions and conclusions. Uncertainties in the projections could either reduce or enhance the estimated effects in specific cases. Nevertheless, as representatives of the world scientific community drawn together in this study, we conclude that many of the serious global environmental effects are sufficiently probable to require widespread concern. Because of the possibility of a tragedy of an unprecedented dimension, any disposition to minimize or ignore the widespread environmental effects of a nuclear war would be a fundamental disservice to the future of global civilization."

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APPENDIX

Selective bibliography

The following is a selective bibliography, illustrating the wide range of recent (i.e. generally since 1982) literature that has been written on the subject of the climatic effects of nuclear war. There are many other specialized papers, articles, assessments, criticisms etc., that are not contained in this list.

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