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REVIEW OF THE IMPLEMENTATION OF THE RECOMMENDATIONS AND DECISIONS ADOPTED BY THE GENERAL ASSEMBLY AT ITS TENTH SPECIAL SESSION: CLIMATIC EFFECTS OF NUCLEAR WAR, INCLUDING NUCLEAR WINTER

Study on the climatic and other global effects of nuclear war

Report of the Secretary-General

1. By its resolutions 40/152 G of 16 December 1985 and 41/86 H of 4 December 1986, the General Assembly requested the Secretary-General, with the assistance of the Group of Consultant Experts chosen by him, bearing in mind the advisability of wide geographical representation and of their qualification in a braod range of scientific fields, to carry out a study on the climatic and potential physical effects of nuclear war, including nuclear winter, which would examine, inter alia, its socio-economic consequences and would take into account the report of the Secretary-General (A/40/449 and Corr.2) and the source documents from which the compilation was prepared, together with any other relevant scientific studies.

2. Pursuant to that request, the Secretary-General has the honour to transmit herewith to the General Assembly the study on the climatic and other global effects of nuclear war.

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ANNEX

Study on the climatic and other global effects of nuclear war

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FOREWORD BY THE SECRETARY-GENERAL

Following the recognition by a number of scientists in 1982 that a major nuclear war might have grave climatic effects with global implications, the General Assembly, by resolution 40/152 G of 16 December 1985, requested the Secretary-General to carry out a study on the climatic and potential physical effects of nuclear war, including nuclear winter, which would also examine its socio-economic consequences. However, owing to the onset of the financial crisis in 1986, the work had to be deferred for a year.

In 1986, by resolution 41/86 H of 4 December, the General Assembly reiterated its request to the Secretary-General, and asked him to transmit the study to the Assembly in due time for consideration at its forty-third session, in 1988.

In accordance with the General Assembly's wishes expressed in resolution 41/86 H, the Group of Consultant Experts appointed by the Secretary-General was composed of scientists from different countries and from a broad range of scientific fields. Some have been involved in research on the subject, while others were addressing the issue for the first time.

The Group's report concludes that a major nuclear war would entail the high risk of a global environmental disruption. The risk would be greatest if large cities and industrial centres in the northern hemisphere were to be targeted in the summer months. In the opinion of the Group, residual scientific uncertainties are unlikely to invalidate this conclusion. The Group indicates that the depletion of food supplies that might result from severe effects on agricultural production could confront targeted and non-targeted nations with the prospect of widespread starvation. The socio-economic consequences would be grave.

For all its apparent robustness, the planet on which we live exists in fragile balance. For the first time in the history of the human race, humanity is now taking actions that, within the time-span of a single generation, are affecting the global environment in fundamental ways. The effects of acid rain and deforestation are plain to see. The future implications of global warming and ozone depletion are just being fully recognized.

The circumstances arising from a nuclear war lie at the extreme end of the range of harmful actions that the human race might inflict on itself. The Group's report serves to confirm that a nuclear war could not be won and must not be fought. It can also be seen as strong argument for the pursuit of sharp reductions in, and ultimate eradication of, nuclear weapons.

The Secretary-General expresses to the members of the Group of Experts his appreciation for their report, which is submitted herewith to the General Assembly for its consideration. It should be noted that the observations and conclusions in the present report are those of the members of the Group of Experts and that the Secretary-General is not in a position to pass judgement on all aspects of the work accomplished by the Group.

LETTER OF TRANSMITTAL

5 April 1988

Sir,

I have the honour to submit herewith the report of the Group of Consultant Experts carrying out the study on the climatic and potential physical effects of nuclear war, including nuclear winter, which was appointed by you in pursuance of paragraph 3 of General Assembly resolution 41/86 H of 4 December 1986.

The consultant experts appointed in accordance with the General Assembly resolution were the following:

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The report was prepared between March 1987 and April 1988, during which period the Group held three sessions, the first from 23 to 27 March 1987 in New York, the second from 18 to 27 November 1987 at Geneva, and the third from 28 March to 1 April 1988 in New York.

The study of such a complex subject could not have been carried out in such a short timescale without significant assistance and expertise from other sources. The members of the Group held two workshop sessions with other experts in order to broaden their knowledge on the subject and found these exchanges to be of great value. In this regard, the Group wishes to express special appreciation to the following: Dr. Thomas C. Hutchinson, University of Toronto, Canada; Dr. Stephen Schneider, National Center for Atmospheric Research, Boulder, Colorado, United States of America; and Dr. Joyce Penner, Lawrence Livermore Laboratory, Livermore, California, United States of America, who took part in a one-day workshop in New York in March 1987.

For the second workshop, special arrangements were made for the Scientific Committee on Problems of the Environment - Environmental Consequences of Nuclear War (SCOPE-ENUWAR) group of scientists to hold a meeting at Geneva in November 1987 at the same time as the United Nations study group. The members of the latter attended the first two days of the SCOPE-ENUWAR discussions and then began their second session with a one-day joint workshop with a number of the scientists. The

Group wishes to express particular thanks to Sir Frederick Warner, Chairman of the SCOPE-ENUWAR Steering Committee, University of Essex, United Kingdom; Dr. Paul J. Crutzen of the Max Planck Institute for Chemistry, Mainz, Federal Republic of Germany; Dr. Mark A. Harwell, Ecosystems Research Center, Cornell University, Ithaca, New York, United States of America; Dr. Michael C. MacCracken, Lawrence Livermore Laboratory, California, United States of America; Dr. Yuri M. Svirezhev, Computation Centre, USSR Academy of Sciences, Moscow, Union of Soviet Socialist Republics; and Dr. Richard D. Turco, R & D Associates, Marina Del Rey, California, United States of America. The United Nations Group is grateful to the International Council of Scientific Unions for the close co-operation and support extended by SCOPE-ENUWAR throughout the work of the Group.

The Group also wishes to express its appreciation for the expert advice and contributions received from a number of United Nations agencies. In addition to Professor Sune Bergström, a member of the Group and also Chairman of the World Health Organization's Management Group, which has made two reports on the effects of nuclear war on health and health services, significant assistance was received from Dr. Francesco Sella, consultant to the United Nations Environment Programme; Professor Pierre Morel, Director, World Climate Research Programme, World Meteorological Organization; and Professor C. C. Wallen, consultant to the World Meteorological Organization.

Finally, the members of the Group of Experts wish to express their appreciation for the assistance that they received from members of the Secretariat of the United Nations. In particular, they wish to thank Mr. Yasushi Akashi, Under-Secretary-General for Disarmament Affairs, Mr. Derek Boothby, who served as the Secretary of the Group, and Dr. Andrew Forester, Dartside Consulting and the University of Toronto, who served as the consultant author for the Group.

The prospects for the planet in the event of a major nuclear war as described in this report are grim. Therefore, it is with little satisfaction that I am able to inform you, on behalf of all members of the Group, that the report has been adopted by consensus.

Please accept, Sir, the assurances of my highest consideration.

(Signed) H. A. NIX
Chairman of the Group of Consultant
Experts to Carry Out a Study on
the Climatic and Other Global
Consequences of Nuclear War

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PREFACE

The possibility that a major nuclear exchange might create conditions causing global climatic perturbation emerged in 1982. In 1984, by resolution 39/148 F, of 17 December 1984, the General Assembly requested the Secretary-General to make a compilation of excerpts of scientific studies on the climatic effects of nuclear war, including nuclear winter. That compilation was published in 1985 as a document of the General Assembly (A/40/449 and Corr.2).

On 16 December 1985, the General Assembly adopted resolution 40/152 G, in which it recognized the necessity for systematic research of the subject and requested the Secretary-General to carry out a study on the climatic and potential physical effects of nuclear war, including nuclear winter, and to transmit the study to the Assembly for consideration at its forty-second session, in 1987. However, owing to the onset of the financial crisis in 1986, the work had to be deferred for a year.

By its resolution 41/86 H of 4 December 1986, the General Assembly once again requested the Secretary-General to carry out the study, with the assistance of a group of consultant experts chosen by him, bearing in mind the advisability of wide geographical representation and of their qualifications in a broad range of scientific fields. The General Assembly requested that the study on the climatic and potential physical effects of nuclear war, including nuclear winter, should examine, *inter alia*, its socio-economic consequences and take into account the Secretary-General's report and the source documents from which the compilation was prepared, together with any other relevant scientific studies.

The Secretary-General was requested to transmit the study to the General Assembly in due time for consideration at its forty-third session, in 1988.

The present report has been prepared pursuant to that resolution. The Group of Consultant Experts has made a measured appraisal of the results of scientific studies that have been and continue to be carried out on this complex subject. To ensure that, as far as possible, the Group's considerations reflect the latest available scientific information, the Group has availed itself of the knowledge and expertise of a wide range of scientific bodies and qualified individuals, in particular those involved in the study on the environmental consequences of nuclear war carried out by the Scientific Committee on Problems of the Environment of the International Council of Scientific Unions (ICSU) (known as the SCOPE-ENUWAR study).

The charge to the Group is a broad one. The specific mandate of the General Assembly in resolution 41/86 H calls for a study of the climatic and potential physical effects of nuclear war, including nuclear winter. The Group, taking note of the resolution as a whole, has interpreted the mandate in its broad sense and therefore included biological effects in its consideration. With such an interpretation, it becomes possible to assess potential socio-economic consequences, as required by the General Assembly.

The Group has chosen to minimize the use of the term nuclear winter, because the term does not do justice to the nature, extent and complexity of the circumstances involved. While temperature reductions would not extend frozen conditions over most of the planet's surface in the event of a nuclear war, the cumulative global effects of a major nuclear exchange involving the large urban and industrial centres and taking place in the northern hemisphere summer would be severe and extensive.

For these reasons, the Group of Experts has chosen as the title of its report "Study on the climatic and other global effects of nuclear war".

I. OVERVIEW, FINDINGS AND CONCLUSIONS

A. Evolution of a new dimension of concern

1. A nuclear war would be totally unlike any previous form of warfare in its immeasurably greater destructive power. Atom bombs of the type used at Hiroshima and Nagasaki represented an increase in explosive power from the equivalent of tons of trinitrotoluene (TNT) to thousands of tons (kilotons). Hydrogen bombs, developed about a decade later, represented an increase from thousands of tons to as much as millions of tons (megatons). Over 50,000 nuclear weapons now exist throughout the world, amounting to an estimated total yield of some 15,000 megatons (about 5,000 times greater than that of all the explosives used in the Second World War).

2. The publication of "The Atmosphere After a Nuclear War: Twilight at Noon" by Crutzen and Birks (1982) marked a turning point in the consideration of the indirect effects of a large-scale nuclear war. They realized that large quantities of light-absorbing smoke particles would be injected into the atmosphere by fires ignited by nuclear explosions. The incoming sunlight, which warms the Earth's surface and provides the energy that drives the atmospheric processes and biological production, would be reduced by the smoke and soot, altering the weather and influencing climate. Further calculations on the amounts of combustible material, smoke emission and radiative properties of the smoke supported the hypothesis. Significant potential effects on natural ecosystems, fisheries and agriculture were recognized. Agricultural supplies for the survivors of the direct effects would be jeopardized.

3. The basic climatic effects of massive smoke injections were further explored in a paper by R. Turco, O. Toon, T. Ackerman, J. Pollack and C. Sagan (1983), known by their initials as the TTAPS group. Using scenarios for smoke and dust production and properties, and modified climate models, TTAPS predicted adverse effects, including coolings of up to 25 to 30 C over the land mass of the northern hemisphere, strong heating and stabilization of the upper troposphere, and accelerated transport of smoke to the southern hemisphere. The darkness, land cooling and radiological effects were potentially so severe that the term "nuclear winter" was coined as a metaphor for the aftermath of a nuclear war involving thousands of megatons of explosives (a sizeable fraction of the existing nuclear arsenals). The TTAPS group did not predict permanent or long-term perturbations, but because of the implied global-scale devastation, the TTAPS authors expressed the hope that "the issues raised here will be vigorously and critically examined".

The TTAPS article was accompanied by a paper (Ehrlich et al., 1983) in which a number of biologists considered the possible widespread impact on natural ecosystems and on agriculture.

4. Examination of the effects on the atmosphere and biosphere was made at a Conference on the Long-term World-wide Biological Consequences of Nuclear War in Washington, D.C., on 31 October and 1 November 1983. The meeting was organized by astronomer Carl Sagan and biologist Paul Ehrlich, with an advisory committee of physical and biological scientists. Soviet work reflecting similar findings was also presented and a teleconference between Washington and Moscow via satellite linkage provided an opportunity for United States and Soviet scientists to exchange views. Participants were informed of the environmental stresses that might result from a nuclear exchange, including substantial surface coolings and intense radioactive fall-out, as well as the direct destruction of societal infrastructure. The Conference also heard discussions of large uncertainties in the new predictions and the need for further research into this important problem.

5. In early 1983, the United States Department of Defense commissioned a major study by the National Research Council of the United States National Academy of Sciences. After stressing limitations imposed by uncertainties, the report concluded as follows:

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

(The Effects on the Atmosphere of a Major Nuclear Exchange, National Academy of Sciences, 1985, p. 6)

The USSR Academy of Sciences also examined the physical, chemical and biological consequences of a nuclear war involving 5,400 megatons of total explosive yield and stated that "the main conclusion from our study is that even the most 'optimistic' scenarios of the consequences of the nuclear conflict (if it is fair to speak of optimism in this case) would inevitably result in a global ecological and demographic crisis" (Ecological and Demographic Consequences of a Nuclear War, Svirezhev et al., 1985; English version, 1987, p. 108). Generally similar conclusions were made in reports by the Royal Society of Canada (1985) and the New Zealand Planning Council (1987), which addressed the implications for Canada and New Zealand respectively.

6. In 1983, the Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions (ICSU) was commissioned to mount a study into the environmental consequences of nuclear war, entitled SCOPE-ENUWAR.

Over 300 scientists from 30 countries participated in the preparation of a 2-volume 882-page report published in 1986, which remains the definitive study. The analysis included an extended study of biological effects, while confirming their overall conclusions on the physical effects. In sum, the report concluded that "... 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" (emphasis in original) (Environmental Consequences of Nuclear War, Pittock et al., 1986, foreword, p. xxvi).

7. Subsequent research employing more realistic three-dimensional models has suggested that temperature decreases would be less than first envisioned. However, these could still be large enough to cause serious global effects on natural and agricultural ecosystems over time spans of months to years.

8. The hypothesis was reviewed in 1986 (Golitsyn and Phillips) and 1987 (Golitsyn and MacCracken) by the Joint Scientific Committee that oversees the World Climate Research Programme of ICSU and the World Meteorological Organization (WMO), which has twice concluded that the prediction of serious temperature changes in the weeks following the generation of 100 to 200 million tonnes of smoke from fires after a nuclear exchange "would not be modified (except in detail) no matter how much success attended major efforts to refine the many uncertainties in the atmospheric calculations" (emphasis added) (Golitsyn and Phillips, 1986, affirmed by Golitsyn and MacCracken, 1987).

9. The SCOPE-ENUWAR project convened workshops at Bangkok, in February 1987, at Geneva, in November 1987, and in Moscow, in March 1988, to consider more recent results. These supported earlier SCOPE-ENUWAR assessments of the impact of nuclear war on the climate. New phases of research were initiated at these workshops, namely, case-studies of the impact of nuclear war on the agricultural systems of specific countries, a more detailed analysis of the sources and behaviour of smoke in the atmosphere and more detailed studies of ionizing radiation in the light of the Chernobyl experience.

10. The effects of nuclear war on health and health services have been studied since 1982 by the World Health Organization (WHO), with the publication of two reports (1984, 1987). The World Health Assembly has recommended that the Organization, in co-operation with other United Nations agencies, continue the work of collecting, analysing and regularly publishing accounts of activities and further studies on the effects of nuclear war on health and health services, the Health Assembly being kept periodically informed.

B. Progress on key scientific issues

11. Earlier estimates of the amount of combustible material (fuel loading) have been refined by successive analyses of production and inventory, for example, the detailed survey of a representative set of targets in the United States (Small et al., 1988). While global estimates of up to 150 million tonnes of smoke that could be released into the atmosphere remain generally credible, recent work has

indicated that these amounts are in the upper range. On the other hand, estimates of the components of smoke emissions produced by burning materials such as petroleum and plastics in large fires have increased substantially. Moreover, as a result of recent measurements in laboratory work and in small-scale fires, estimates of the ability of smoke produced in urban fires to absorb sunlight have increased by as much as three times over some earlier calculations. This dark, sooty component of smoke emissions is now recognized as the most important factor with regard to effects on the atmosphere and climate, and accordingly much of the recent research has focused on the characteristics of soot particulates.

12. This large amount of smoke and soot would absorb a substantial fraction of incoming solar radiation over much of the northern hemisphere. Estimates of the reduction of insolation vary considerably, depending on the scenario: in instances of concentrated smoke, the available light at the surface might be only 1 per cent of normal for periods of a few days, and less than 20 per cent of normal for a few weeks or more.

13. Smoke injected by large fires can initially reach altitudes of as much as 15 kilometres, although most will be in the 5 to 10 kilometre range. The rising smoke eventually stabilizes, allowing the smoke to spread laterally at the stabilization height. Subsequent heating of the smoke by absorption of solar radiation can result in the further ascent of the smoke particles. Recent modelling studies indicate that such large-scale "lofting" from mid-altitudes during the northern hemisphere summer may carry a large fraction of the smoke as high as 30 kilometres. The self-induced lofting of nuclear war smoke suggests that its residence time in the stratosphere could be greatly increased, that substantial quantities of smoke could be transported to the southern hemisphere and that the integrity of the stratospheric ozone layer could be threatened.

14. The removal efficiency of smoke by clouds and precipitation (referred to as "scavenging" and "removal") is presently assumed to be in the range of 30 to 50 per cent during the first few days following smoke generation, although uncertainties are large and the actual amounts could be more or less. The removal processes include the "prompt" scavenging in "black rain" directly over the conflagrations expected after a nuclear exchange, as well as subsequent scavenging by precipitation downwind of the fires. Scavenging of the smoke would decrease the potential for light reductions and patchiness would produce lighter and darker regions locally. Recent laboratory and field measurements of smoke properties suggest that the removal efficiency for the the blackest, sootiest smoke may be smaller than is currently assumed. Accordingly, further refinement of the smoke (soot) scavenging estimates is needed.

15. New laboratory studies indicate that soot reaching the stratosphere (by direct injection and self-lofting) is not likely to be rapidly decomposed by reacting with ozone and that this process may take about a year or more. This important result implies that soot clouds could be quite stable in the upper atmosphere, allowing them to spread globally, with the potential for long-term effects on the global climate.

16. Although still highly simplified, significant advances have been made in modelling the atmospheric response to massive smoke injections. The laws governing

relevant atmospheric processes are cast in mathematical form and the resulting equations solved on high-speed computers. Such computations using advanced general circulation models are now capable of representing, in detail, the changes in solar and thermal infra-red radiation transfer, the hydrologic cycle, as well as atmospheric circulation and dynamics. Such models, adapted for simulation of "nuclear winter" conditions, have been developed at the Los Alamos National Laboratory, the National Center for Atmospheric Research and the Lawrence Livermore National Laboratory in the United States, the Computing Centre of the USSR Academy of Sciences in the Soviet Union, the United Kingdom Meteorological Office and the Commonwealth Scientific Industrial Research Organization in Australia. Work on these models has led to significant general advances in climate modelling capabilities. These models confirm the possibility that sub-freezing temperatures may be reached in localized regions even in summer. They also show substantial reductions of precipitation and suppression of the summer monsoon, even with relatively small amounts of smoke. Moreover, the potential for climatic effects lasting for a period of one year or more have been recognized, with the possibility of average global temperatures decreasing by several degrees, which could have a major effect on agriculture.

17. There is now ample observational evidence that the smoke from natural forest fires and dust, if present in sufficient quantities, can cause decreases of several degrees in daytime temperatures in a matter of hours to days. These reductions are reproduced well by the models, which means that the basic physical processes are sufficiently understood. This also increases confidence in the model results showing more severe temperature reductions if very large quantities of smoke were injected into the atmosphere by fires started after a nuclear exchange.

18. The injection into the stratosphere of the nitrogen oxides produced in a nuclear fireball and air from the lower atmosphere, which is low in ozone, the displacement of the ozone-rich lower stratospheric air and the dependence of chemical reaction rates on the anticipated temperature increase of the stratosphere are also being studied with respect to their potential for reducing the amount of stratospheric ozone. Ozone depletion would imply increased damaging ultraviolet solar radiation for several years following a nuclear exchange. Current estimates are that ozone reduction could be very substantial, of the order of 50 per cent. Because of the great potential importance of this problem, it urgently needs further study.

19. The electromagnetic pulse caused by high-altitude nuclear detonations can disrupt and damage a wide variety of electrical and electronic components and devices, leading to the loss of power, communications and other services out to distances of thousands of kilometres. This would represent a significant additional disruption to the infrastructure on which survivors would have to rely.

20. Early radiation, along with blast and heat, would kill many people in the immediate vicinity and destroy the housing, sanitation, transport and medical facilities. Beyond the area of devastation, nuclear fall-out arising from the explosions themselves and from the destruction of nuclear installations would spread globally and be a source of continuous radiation exposure for years. The long-term consequences (e.g. cancers, malformations and possibly genetic effects) among the survivors of the initial radiation burst and those exposed to fall-out

would be significant, but their importance would be considerably smaller than consequences from the early effects and those resulting from disruption of basic infrastructure, including medical and food distribution services, for months and perhaps years after the event.

C. Findings and conclusions

21. The Group's examination of the evolution of scientific thought on the global environmental consequences of a nuclear war reveals a clear convergence towards consensus. The criticisms and objections that have been raised from time to time - mostly concerned with uncertainty and limitations of early models - have been reviewed by this and other expert groups (e.g. the Joint Scientific Committee, see Golitsyn and MacCracken, 1987) and do not invalidate the conclusion that a large-scale nuclear war could have a significant effect on global climate.

22. The scientific evidence is now conclusive that a major nuclear war would entail the high risk of a global environmental disruption. The risk would be greatest if large cities and industrial centres in the northern hemisphere were to be targeted in the summer months. During the first month, solar energy reaching the surface in mid-latitudes of the northern hemisphere could be reduced by 80 per cent or more. This would result in a decrease of continental averaged temperatures in mid-latitudes of between 5 and 20 C below normal within two weeks after the injection of smoke during summer months. In central continental areas individual temperature decreases could be substantially greater. Three-dimensional atmospheric circulation models with detailed representations of physical processes indicate regional episodes of sub-freezing temperatures, even in summer. These temperature decreases are somewhat less than those suggested by earlier less complex atmospheric models, but the agricultural and ecological effects are no less devastating. Recent work presented at the SCOPE-ENUWAR workshop in Moscow in 1988 suggests that these effects might be compounded by a decrease in rainfall of as much as 80 per cent over land in temperate and tropical latitudes. The evidence assessed to date is persuasive that residual scientific uncertainties are unlikely to invalidate these general conclusions.

23. Beyond one month, agricultural production and the survival of natural ecosystems would be threatened by a considerable reduction in sunlight, temperature depressions of several degrees below normal and suppression of precipitation and summer monsoons. In addition, these effects would be aggravated by chemical pollutants, an increase in ultraviolet radiation associated with depletion of ozone and the likely persistence of radioactive "hotspots".

24. The sensitivity of agricultural systems and natural ecosystems to variations in temperature, precipitation and light leads to the conclusion that the widespread impact of a nuclear exchange on climate would constitute a severe threat to world food production. The prospect of widespread starvation as a consequence of a nuclear war would confront both targeted and non-targeted nations. This would be aggravated by the increasing dependence of food production on inputs of energy and fertilizers and the dependence of food distribution and availability on a smoothly functioning societal system of communications, transportation, trade and commerce. The human impact would be exacerbated by an almost complete breakdown of health

care in targeted countries and the likelihood of an increase in damaging ultraviolet radiation. The direct effects of a major nuclear exchange could kill hundreds of millions: the indirect effects could kill billions.

25. The socio-economic consequences in a world intimately interconnected economically, socially and environmentally would be grave. The functions of production, distribution and consumption in existing socio-economic systems would be completely disrupted. The severe physical damage from blast, fire and radiation in the targeted countries would preclude the type of support that made recovery possible following the Second World War. The breakdown of life support systems, communications, transportation, the world financial and other systems would compound the difficulties caused by food shortages in non-targeted countries. Long-term recovery would be uncertain.

26. The immediate and direct effects of nuclear explosions and the global, environmental consequences of a major nuclear war constitute a continuum. Each would exacerbate the other. Moreover, there would be synergy within each aspect as well as between them so that the integrated total effect of fire, blast and radioactivity would be greater than their sum. Similarly, temperature decrease, brief sub-freezing episodes, diminished precipitation, suppressed monsoons and increased ultraviolet radiation would interact in a manner that would compound their separate effects. The global, environmental disruption resulting from a major nuclear war would be inseparably related to its direct and localized effects. Both should be considered in resolving policy issues of nuclear weaponry and should be the concern of all nations.

27. The possibility exists that further global environmental consequences of a major nuclear exchange may yet be identified. The Group believes that the co-operative, international scientific effort that has identified this new dimension of nuclear warfare should be continued to refine present findings and to explore new possibilities. For example, there is a need to resolve the emerging issue of a possibly massive depletion of ozone as a result of major nuclear war and the ensuing increase in ultraviolet radiation with potentially serious consequences for exposed living organisms.

28. The scientific advances that have led to a clearer understanding of the global consequences of major nuclear war should be pursued internationally. They should also interact strongly with the analysis of public policy decisions on these issues, which have potential implications for non-combatant nations as well as for nations that might be in conflict. The discussion of these matters has underscored the importance of the dialogue between the world scientific community and public policy makers - a dialogue that has illuminated this general issue during the 1980s.

II. ATMOSPHERIC AND CLIMATIC CONSEQUENCES

A. Introduction

29. A nuclear war would be totally unlike any previous form of warfare in its immeasurably greater destructive power. Atom bombs of the type used at Hiroshima and Nagasaki represented an increase in explosive power from the equivalent of tons of trinitrotoluene (TNT) to thousands of tons (kilotons). Hydrogen bombs, developed about a decade later, represented an increase from thousands of tons to as much as millions of tons (megatons). Over 50,000 nuclear weapons now exist throughout the world, amounting to an estimated total of some 15,000 megatons (about 5,000 times greater than that of all the explosives used in the Second World War).

30. Radioactive materials from nuclear explosions can be transported to great distances from the site of the explosion, and people far removed from the site of the detonations would be exposed to ionizing radiation. The genetic and teratogenic effects of the latter may even be manifest in succeeding generations.

31. The large amounts of dust and smoke injected into the atmosphere from ground and low-altitude bursts and fires in a major nuclear war might cause serious climatic changes not only in the countries where the war takes place but also in others remote from hostilities. The present report reviews the results of a number of studies on the potential climatic impact of multiple nuclear detonations.

32. The United States National Academy of Sciences 1975 report on the atmospheric impacts of nuclear warfare concluded that many of the chemicals, particularly nitrogen oxides, created by nuclear explosions would affect the stratospheric ozone layer, which shields the Earth's surface from an excess of harmful ultraviolet radiation and which is instrumental in maintaining the normal temperature, structure and circulation of the atmosphere. It also considered the effect of dust raised by explosions, making the analogy with the effects of particles emitted by volcanic eruptions, and concluded that there could be a drop in global temperature of about 1 C caused by the resulting diminution of sunlight at the Earth's surface.

33. Years after the development of nuclear weapons, new indirect environmental impacts of a major nuclear war are emerging. In 1945 attention was focused on radiation sickness, in the 1950s on the long-range transport of radioactive fall-out, in the early 1960s on the electromagnetic pulse and in the 1970s the depletion of the ozone layer by the injection of nitrogen oxides into the stratosphere. In 1982-1983 the potential for nuclear war to effect a major climatic change became apparent. It is possible that other unanticipated effects remain to be discovered. For example, it has been suggested that the ozone depletion might be more severe than is now estimated. There may also be near-surface temperature inversions that would trap many toxic substances in the lower atmosphere and prevent their dispersion, thus greatly increasing the toxic exposure to plants, animals and especially humans.

34. In 1981-1982, the Royal Swedish Academy of Sciences undertook a comprehensive review of the global social, economic and environmental effects of nuclear war,

publishing the results of a series of specifically commissioned studies in its journal Ambio in 1982 (published afterwards in book form as The Aftermath, Peterson, 1983). These included a paper by Paul Crutzen and John Birks on the effect of nuclear explosions on the atmosphere. They confirmed that there was a possibility that the ozone layer could be harmed and that there could be an impact on climate and weather. The authors went on to consider the possibility that a major nuclear attack would ignite widespread fires and that "large quantities of highly sunlight-absorbing, dark particulate matter 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 lands, and forests ... such fires would strongly restrict the penetration of sunlight to the earth's surface and change the physical properties of the earth's atmosphere" (Crutzen and Birks, 1982). Their report, "The Atmosphere After a Nuclear War", bore the subtitle "Twilight At Noon".

35. They made tentative suggestions concerning the effects on the energy balance of the Earth, natural ecosystems, fisheries, agriculture and society, enunciating the proposition that a large-scale nuclear conflict might alter climate. Following the publication of this seminal paper, work began in the United States and the USSR on climatic effects of large smoke injections into the atmosphere and their environmental consequences.

36. Effects on the atmosphere and biosphere were first publicly considered in the two-day conference held in Washington, DC, in the autumn of 1983. The two main reports, published shortly afterwards in the journal Science (the so-called TTAPS paper, that is, Turco et al., 1983, and the paper by Ehrlich et al., 1983) were presented on the first day of the meeting. Similar presentations on the reduction in temperature were made by Aleksandrov, Schneider and Golitsyn (who argued in addition that precipitation and the monsoon would be suppressed). The main reports, together with other presentations made at the meeting and the discussions accompanying the proceedings, were subsequently published as the book The Cold and the Dark: The World After Nuclear War (Ehrlich et al., 1984). The conference was concluded with a televised link between Washington and Moscow in which leading Soviet and United States scientists discussed the issues.

37. The TTAPS paper was cautious, concluding as follows:

> "Our estimates ... 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 ... or the effect of such changes on the maintenance and dispersal of the initiating dust and smoke clouds. Nevertheless, the magnitude 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." (Turco et al., 1983)

38. Criticism was voiced on various scientific grounds: for example, no account was taken of the moderating influence of the oceans. This was a limitation of the one-dimensional modelling method used and as such was readily acknowledged by the

authors. Although a one-dimensional model is not, in this instance, an adequate substitute for a more sophisticated simulation, it is a useful and necessary step towards a more comprehensive treatment of the problem. The inclusion of particulate material and aerosols in three-dimensional models, which had been used only for simulating natural climatic phenomena, required major technical developments.

39. The challenge set by Crutzen and Birks and the authors of the TTAPS paper was met by the scientific community. Many atmospheric scientists set about testing the assumptions and implications. As Schneider and Londer (1984) commented, "several physical science groups did their best to find flaws in the TTAPS analysis ... to see if any neglected factors could make the large surface cooling effects disappear - not to negate the work of the TTAPS team, but rather to insure the credibility of the results".

40. This led to major reports on the subject by the United States National Research Council (1985), the Institute of Medicine (1986) and the Royal Society of Canada (1985). Soviet work is described in the books The Night After, Climatological and Biological Consequences of Nuclear War (Velikhov, 1985), Ecological and Demographic Consequences of a Nuclear War (Svirezhev et al., 1985), Global Climatic Catastrophes (Budyko et al., 1986), and Possible Ecological Consequences of Nuclear War for Atmosphere and Climate (Kondratyev and Nikolsky, 1986). The most comprehensive study has been undertaken by ICSU through its SCOPE-ENUWAR programme. This has involved approximately 300 scholars from the international community, representing a wide range of disciplines, and provides an extensive reference source on the subject. This work, Environmental Consequences of Nuclear War has been published in two volumes, Volume I. Physical and Atmospheric Effects (Pittock et al., 1986) and Volume II. Ecological and Agricultural Effects (Harwell and Hutchinson, 1986), with a companion, summary volume written for the non-expert Planet Earth in Jeopardy (Dotto, 1986). WHO has revised its 1984 report to include an assessment of the climatic effects in Effects of Nuclear War on Health and Health Services (WHO, 1987). The perspective from the Southern Hemisphere has recently been addressed by the New Zealand Planning Council in New Zealand After Nuclear War (Green et al., 1987) and in Nuclear Winter in Australia and New Zealand: Beyond Darkness (Pittock, 1987). In parallel to these studies, a number of Governments, notably those of the Soviet Union and the United States, have sponsored broad-based research efforts, particularly on the properties of smoke in the atmosphere and numerical simulations of atmospheric aerosols in atmospheric circulation models.

B. Technical issues

1. Dust

41. Dust is raised into the atmosphere by surface and near-surface nuclear explosions. The SCOPE-ENUWAR study (Pittock et al., 1986) estimated that up to several tens of millions of tonnes of sub-micron dust particles (those having a diameter of less than 1 micrometre) could rise into the upper troposphere and stratosphere where they could remain for a month or more. Dust effectively scatters sunlight, reflecting a portion of the incoming solar radiation back to space.

42. The processes of scattering (reflection) and absorption of sunlight high in the atmosphere reduce the amount of solar radiation reaching the Earth's surface. Dense patches of dust could cause significant reduction of sunlight reaching the surface underlying the cloud. If the dust were dispersed uniformly over the northern hemisphere, it could still reduce the light received at the surface by 10 per cent or more.

2. Combustion and fuels

43. Fuels, such as coal, oil and natural gas, or, in the general sense used here, anything that burns in a large urban-industrial fire (wooden construction materials, paper, plastics, asphalt roofing, bitumen road surfaces) or a wildland fire (trees, crops and other vegetation), are largely comprised of complex chemicals consisting mostly of carbon and hydrogen.

44. Under ideal conditions, when hydrocarbon molecules are oxidized (burned) in an unrestricted supply of oxygen, the reaction will be complete and the products will be carbon dioxide and water vapour. However, such ideal conditions seldom exist and, in normal fires, the oxidation usually proceeds to varying stages of completion, depending upon environmental conditions, and produces particulate residues called soot or smoke in addition to these gases. At high temperatures, in a flame, some of the hydrogen and carbon in the fuel may be liberated without oxidation (pyrolysis), yielding a pure carbon soot resembling graphite or lamp black. At lower temperatures, in a smouldering combustion, oxidation is incomplete and a large number of partially oxidized residues remain. These usually consist of hydrocarbons, albeit of a simpler chemical nature than the original fuel.

45. The relatively pure elemental carbon soot and the products containing a high proportion of hydrocarbons have very different chemical and physical structures. They behave differently in the atmosphere and are able to absorb much more sunlight than low carbon smokes. The fuel may also contain other chemicals that are not oxidized or are oxidized to form a variety of molecules with different properties.

46. Estimates of the amount and nature of the materials ignited in a nuclear war have been made using three different approaches. Turco et al., (1983) and the National Research Council (1985) studies estimated the average loading of combustible material present in a unit area of various targets and then scaled upwards by multiplying by the area that would be exposed to a thermal flux capable of causing ignition for an assumed distribution of targets. The area exposed to the ignition thermal flux depends upon meteorological conditions (humidity, turbidity), the altitude of the detonation and the yield of the warhead. A 1 megaton explosion would ignite many materials over an area of 50-1,000 square kilometres, but because of the probable overlapping of explosions, the limited size of urban areas and other factors, values between 250 and 500 square kilometres ignited for 1 megaton (varying with the square root of yield) are usually considered representative. Penner (1986) showed that fuel loadings were originally overestimated and are still incompletely known. Because the targeting pattern (and therefore the overlap between the resulting fires) can never be known with certainty, this method of calculation is relatively inaccurate.

47. Another method used by Crutzen et al. (1984) and Pittock et al. (1986) developed inventories of combustible materials in potential target areas and made assumptions concerning how much of the fuel would burn.

48. A third approach is based on detailed analyses of representative targets (Small et al., 1988). This estimate indicates that 40 million tonnes of smoke would be produced after a major attack against the United States, a third of which would come from burning petroleum, gas and coal and would consist of sooty (high carbon content) particles that absorb solar radiation efficiently.

49. Two independent estimates of fuel inventories suggest that 6,000-17,000 million tonnes of cellulosic materials (wood, paper, etc.) and 1,300-1,500 million tonnes of petroleum and plastics can be found in the areas covered by the countries of the North Atlantic Treaty Organization (NATO) and the Warsaw Treaty Organization. The range of estimates for cellulose materials results largely from differences in assumptions about the amount of wood used in construction in Europe and the Soviet Union, the usage and mean effective lifetime of wood and wood products in the environment. Estimates of the total fuel available for burning in the Warsaw Treaty Organization and NATO countries are 10,000 million tonnes, with an uncertainty of about 50 per cent.

50. Because petrochemical refineries and stores are of strategic importance, they would be likely targets and this has been assumed in most of the war scenarios. Turco (1987) presented data showing that two thirds of the global petrochemical stocks (approximately 500 million tonnes) are located in about 200 discrete areas and, under ideal conditions, could be ignited by only a few hundred small or medium-size warheads with a total yield in the order of a few megatons. This would produce sufficient black, sooty smoke (see below) to cause a significant climatic effect.

51. The initial concern for potential climatic effects of nuclear war was based on the estimates of the smoke emitted by burning woodlands (Crutzen and Birks, 1982). Many potential targets, such as missile silos, air bases and command centres, are located in grassland or agricultural areas where the fuel loading is low and only a few million tonnes of smoke would be generated (Small and Bush, 1985). The SCOPE-ENUWAR study (Pittock et al., 1986) discusses factors that may raise these estimates, but it appears that live vegetation may not be ignited (Bush and Small, 1987). Soot might be produced by the direct gasification (pyrolysis) of organic material by the thermal pulse from the fireball, perhaps liberating about 20 million tonnes of elemental carbon (Gostintsev et al., 1986; Golitsyn, 1986). If lifted by fireballs into the upper troposphere and lower stratosphere, this alone could cause significant climatic effects. However, the process of carbon emission by pyrolytic reactions under the influence of the explosion thermal flux and subsequent reactions of carbon with ambient air are not well understood.

3. Fires

52. The size, nature and number of the fires are dependent on the magnitude of the nuclear conflict and choice of warheads and targets selected. The tremendous incendiary potential of nuclear weapons and the environmental conditions in the target area can lead to superfires or fire storms that can cause complete combustion of fuel and total devastation over a large area.

53. Evidence from Hiroshima and Nagasaki suggests that mass fires can be ignited by a thermal fluence in the range of 7-20 calories per square centimetre (cal cm^{-2}). The higher value is probably an overestimate, many ignitions taking place at 7-10 cal cm^{-2}. Using the conservative value of 20 cal cm^{-2}, two independent studies suggest that there would be immediate ignition of 250-375 square kilometres for each megaton yield (a much greater area if a lower flux is used as a basis for the calculation). When the spreading of fires is taken into account the burned area could increase greatly: it reached 1,200 square kilometres per megaton in the low-yield Hiroshima explosion (Pittock et al., 1986). Recent simulations relate the fires to weapon yield, slant range, atmospheric conditions, fuel character, topography, presence of firebreaks and other factors (Woodie et al., 1984).

54. In wildlands, much of the organic material is potentially combustible and it is reasonable to suppose that the blast wave might disperse and splinter the fuels, making them even more flammable. This is not necessarily so in the case of suburban and urban areas, which contain large quantities of non-combustible material such as plaster and concrete. Blast may damage non-combustible structures, opening them up to expose more fuel to the fire. Alternatively, it may bury potentially flammable materials under refractory rubble. Possibly both processes might occur, depending upon the specific local circumstances at any point.

55. Finely divided refractory and non-combustible mineral material (concrete, brick dust, plaster, soil, etc.) will be entrained within the fire. The effects of this on the combustion process, particularly the radiative energy feedbacks within the flame, are not known.

4. Smoke emissions

56. The emission factor (amount of fuel converted into airborne particulate matter such as soot and smoke) is represented as a ratio or percentage, e.g. a 5 per cent smoke emission factor means that 50 grammes of smoke are generated from each kilogramme of fuel. This factor and the chemical and physical properties of that smoke are important considerations in assessing the impact on the atmosphere.

57. The emission factor and the carbon content of the smoke are not accurately known and even when they have been determined under experimental conditions the estimates vary by a factor of two at least (Pittock et al., 1986; Penner, 1986). More recent research in the United States and the USSR (report of the SCOPE-ENUWAR workshop at Geneva, 16-20 November 1987) shows that the larger the fire the greater the emission factor. It also increases with a decrease in ventilation. Under the

wide range of environmental conditions that might be expected in a nuclear attack, the emission factors and smoke content would introduce considerable uncertainty.

58. Two major studies have estimated the overall emission factors from urban fires as 3.3-4.0 per cent, with a carbon content of the emissions being estimated conservatively at 20 per cent, more generally in the range of 33-80 per cent (Pittock et al., 1986). These estimates include assumptions concerning the proportions of fuel types because different materials have different emission factors, e.g. 1.5-3.0 per cent for wood, approximately 5 per cent for plastics and 6-10 per cent for fuel oils (Pittock et al., 1986; Crutzen, 1987).

59. Comprehensive estimates (Turco et al., 1983; Crutzen et al,. 1984; National Research Council, 1985) of the smoke that might be produced by a major nuclear war with a total explosive yield of 5,000-6,500 megatons vary considerably, ranging from 50 to 150 million tonnes after allowance for precipitation scavenging. Given their differing assumptions about emission factors and fuel mix these estimates agree fairly closely that about 30 million tonnes of elemental carbon would enter the atmosphere from burning urban-industrial areas (Pittock et al., 1986).

60. A number of groups have measured the smoke yield from a wide variety of substances in small-scale experimental fires. Although there are doubts that such fires adequately represent the combustion that would take place in the large fires resulting from a nuclear attack, these experiments have given improved insight into the combustion process. The smoke yield was found to be 1.5 and 4.0 per cent for wet and dry wood respectively and may be as large as 11 per cent for plastics (Andronova et al., 1986) although this value may fall to 3 per cent under freely ventilated conditions (Mulholland, 1986; Patterson et al., 1986).

61. The material consumed in urban fires would be a mixture of various fuels. A fuel mixture representing that found in a typical city, comprising 60 per cent wood, 20 per cent paper, 15 per cent fabrics and 5 per cent plastics, yielded an overall emission factor of 5-6 per cent (Andronova et al., 1986). Burning petrochemicals would produce black smoke with an emission factor in the range 3-5 per cent from relatively small fires (Andronova et al., 1986) up to in excess of 10 per cent for large fires (Zak, 1987). These data are in close agreement with those reviewed by Penner (1986) and about 50 per cent higher than those used in the 1985 National Research Council study.

62. The SCOPE group concluded that if about one quarter of the 2,700 million tonnes of stored combustible materials were burned, they would release about 80 million tonnes of smoke, containing 45 million tonnes of elemental carbon to the atmosphere. This might be achieved by total combustion of less than 100 very large cities and their associated strategic fuel reserves and takes no account of smoke emissions from fires in rural areas resulting from counterforce attacks against silo fields.

5. Optical properties of smoke

63. The optical properties of the smoke emitted by fires depend upon the size, structure and composition of the smoke particles, which, in turn, are determined by material and conditions of burning. Extensive studies of smoke properties have been undertaken only recently in the United States, the USSR and the United Kingdom.

64. Smoke absorbs and scatters light. The greater the absorption relative to scattering, the blacker the smoke appears; the greater the scattering, the more white the smoke appears. Both processes are intimately connected. Attenuation of light is an exponential function of the amount of smoke in the atmosphere. It also depends on the wavelength of light and on the physical and chemical properties of the particles.

65. Smoke particles produced by burning oil products have branched chain structures that increase their absorption per unit mass of smoke. Recent measurements have shown that absorption by carbon particles may be at least twice as great as the values used in earlier studies (e.g., National Research Council, 1985). It is now thought that the total quantity of smoke emitted in a major nuclear war would be less than originally estimated. However, the attenuation of sunlight would remain a major problem because the carbon content of the smoke and its ability to absorb solar radiation would be greater than suggested by earlier studies.

66. New measurements (Andronova et al., 1986; Golitsyn and MacCracken, 1987) of the ratio of absorption of solar radiation to the absorption of thermal radiation emitted by the Earth's surface and atmosphere suggest that, for many types of smoke, the long-wave emissions to space would not be significantly interrupted. This would allow the Earth's surface to cool in a manner similar to that of a clear night despite the presence of the smoke. More work is required on this important aspect of smoke and its effect on radiative energy transfer in the atmosphere.

67. To study the sensitivity of climate to various amounts of smoke in the atmosphere, it was agreed at the Bangkok SCOPE-ENUWAR workshop (1987) to consider three cases of small, medium and large amounts of smoke. These amounts averaged over the northern hemisphere and accounting for absorption and scattering can reduce the solar radiation at the surface, respectively to about 60, 10 and 1 per cent of the normal.

6. Altitude of smoke injection

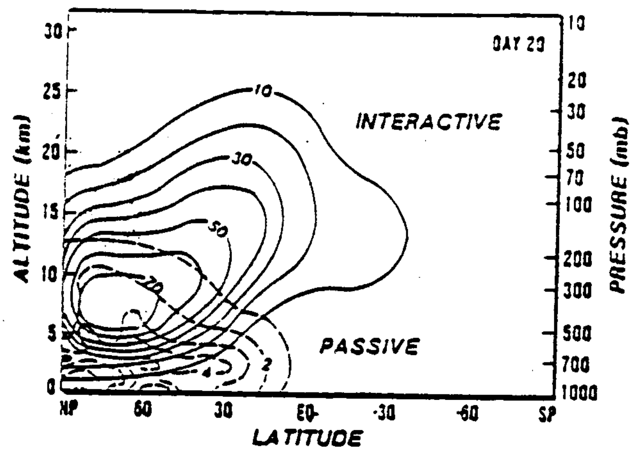
68. Observations suggest that smoke from localized forest fires usually rises to an altitude of 2-3 kilometres but that, if the fire is large and well ventilated and the air is humid, it may reach 5-6 kilometres. Smoke plumes from very large forest fires and urban fires observed during the Second World War sometimes reached in excess of 10 kilometres. It is probable that smoke from nuclear attacks would therefore reach the upper troposphere, and some may enter the stratosphere (Golitsyn and MacCracken, 1987).

69. Numerical simulations based on modified convective cloud models have been used to estimate plume injection heights for a range of fire intensities and meteorological conditions. These support the view that smoke from very intense fires may enter the lower stratosphere up to heights of about 15 kilometres, but that smoke from fires of moderate intensity may only reach the middle to top of the troposphere. Plume rise may be affected by the generation of vortices in fire storms, but it is not clear whether this effect would be positive (Turco et al., 1983) or negative (Tripoli and Kang, 1987). Wind shear would limit the plume rise or reduce the subsidence of the plume from its peak height over the fire. Computer simulations suggest that the height of the plume is governed by the total heat release, or power of the fire, not by the area of the fire (Small and Heikes, 1988). Meteorological conditions are also important, particularly the stability of the atmosphere and its humidity, because moisture can release considerable energy in the form of latent heat, which reinforces buoyancy of the plume (Pittock et al., 1986; Golitsyn and MacCracken, 1987).

70. One of the most significant findings is that smoke becomes heated through the absorption of solar radiation and the air containing it becomes more buoyant. This process, called lofting, was predicted by three-dimensional atmospheric model simulation in which provisions were made for the transport of the smoke by the atmospheric circulation (Malone et al., 1986) (see figures 1 (a) and (b)). Lofting would cause soot and smoke to reach much higher altitudes than the initial injection height predicted on the basis of the characteristics of the fire.

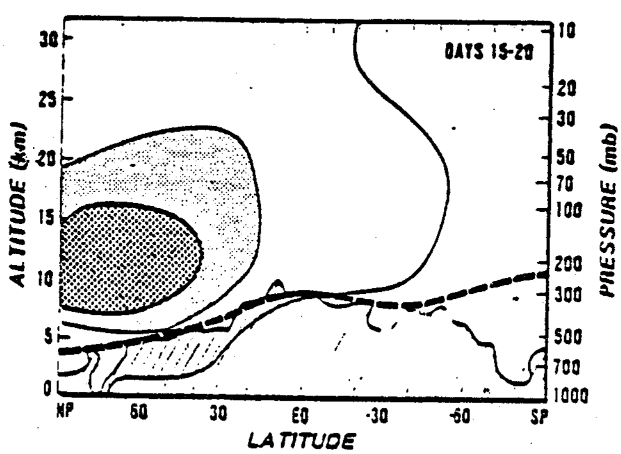
71. Certain assumptions have an important influence on the computed climate impacts. The higher the smoke, the less likely it is to be removed by precipitation. The higher the layer of the atmosphere in which the solar radiation is absorbed, the less effective will be the containment of the long-wave thermal radiation emitted from the elevated smoke layer and the more the surface will cool. As fire plume models improve, better estimations of smoke injection altitude may be expected.

Figure 1 (a). Comparison of the vertical cross-sections of smoke mixing ratios for the passive (dashed lines) and interactive (full lines) smoke cases of Malone et al., (1985) on day 20 (units are 10^{-9} g/g)



Source: A. B. Pittock, et al., Environmental Consequences of Nuclear War, vol. I (Chichester, 1986), p. 190.

Figure 1 (b). Vertical cross-section of the atmosphere, showing the modified position of the tropopause (heavy dashed line) and the precipitation distribution (cross-hatched region below the tropopause), both averaged over days 15-20, and the smoke distribution at day 20 (stippled area mainly above the tropopause)



Note. Results are for the July interactive-smoke case with 170 million tonnes of smoke injected between 0 and 9 km altitude (from Malone et al., 1985).

Source: A. B. Pittock, et al., Environmental Consequences of Nuclear War, vol. I (Chichester, 1986), p. 191.

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7. Scavenging and removal of smoke particles

72. Many processes govern the fate of the smoke particles, from their generation in fires to their spreading over scales that can affect global weather and climate. Rising from the fires, the smoke particles can coagulate (coalesce), increasing their mean size and changing the size distribution. The rising plume can draw in ambient water vapour along with the air. Expansion of the rising plumes leads to cooling and water vapour condensation on those smoke particles, which can act as condensation nuclei. The fraction of particles on which water can condense is partly dependent on the carbon content of the particles: the greater the amount of carbon, the more hydrophobic (water repellent) the particles. Smoke particles (low carbon) are therefore more efficient condensation nuclei than soot (high carbon). However, the composition of the aerosol particles produced by the sort of fires expected from nuclear detonations under a wide variety of conditions is poorly understood. Water droplets formed on the smoke particles lofted to high altitude could become ice particles; they may be incorporated into larger water droplets and so be scavenged and removed from the air by precipitation.

73. The extent of condensation, which depends upon atmospheric humidity, fire intensity, local meteorological processes and other factors, determines whether precipitation occurs, and if the captured particles that have been scavenged by cloud droplets are carried to the ground as black rains (such as fell at Hiroshima) or released back to the atmosphere. Particles that emerge from the water cloud and avoid precipitation scavenging may be processed in such a way that their shape is changed. In particular, the re-evaporation of water from the particles as they emerge from the cloud may make them more compact, with a consequent change in their optical properties. Recent experimental results (Harrison, presented at the SCOPE-ENUWAR workshop, Geneva, 1987) suggest that the changes may not be as great as previously thought.

74. The TTAPS study (Turco et al., 1983) assumed that half the initial smoke would be removed immediately from the atmosphere through these processes. The NRC (1985) report estimated a possible range of early removal to be 10 to 90 per cent. Recent measurements (reported by Turco at the SCOPE-ENUWAR workshop, Geneva, 1987) suggest that, for moderate sized oil pool fires of an area of 170 square metres, most of the scavenging processes described above operate weakly and that removal of sooty smoke through condensation is small. Thus, the present scientific view is that scavenging is likely to be of less importance in the removal of smoke than first thought. However, these issues remain a source of uncertainty and need further study.

8. Reductions in light

75. Soot, smoke and dust particles (collectively called aerosols here, although this term technically includes liquid droplets) can absorb and scatter sunlight in the atmosphere. This may cause significant changes in the radiative energy balance, circulation of the atmosphere, alterations in climate and a reduction in both sunlight and temperature at the Earth's surface. The extent to which such perturbations occur depend upon the amount of aerosol, its location and residence time in the atmosphere and the chemical and physical properties of the particles.

76. In the normal atmosphere, 30 per cent of the sun's energy, comprising visible and short-wave radiation, is reflected by clouds and the Earth's surface, about 25 per cent is absorbed within the atmosphere and the balance of 45 per cent is absorbed by the ground. The energy absorbed by the Earth's surface is subsequently released back to the atmosphere as infra-red (long wave) radiation that is largely absorbed by greenhouse gases in the atmosphere; sensible heat through contact between the atmosphere and surface; and by release of latent heat when evaporated water condenses again in the atmosphere. The totality of the energy absorbed by the Earth from solar radiation is eventually lost to space in the form of long-wave emitted radiation.

77. The presence of an aerosol layer that can absorb and scatter the solar radiation above the clouds and greenhouse gases places a constraint on the radiative balance that could have far-reaching consequences. The central proposition of the so-called "nuclear winter" hypothesis is that there would be a reduction in the energy flux to the Earth's surface causing cooling and darkening. Further, the solar energy absorbed by the smoke would cause heating of the atmosphere leading to major changes in thermal structure and circulation and a reduction in precipitation.

9. Numerical simulation

78. Numerical climate models consist of a set of equations describing the physical laws governing the motion and temperature of the atmosphere and ocean, transformations between water vapour, liquid and ice, exchanges of energy and interactions between the atmosphere and the land and ocean surfaces. The ability to describe all these processes and to solve the equations on a computer is limited, so that any climate model, even the most advanced atmospheric circulation model, is only an approximate representation of reality. How well a particular model simulates the reality of the present (normal) climate can be tested by comparing model results with available observations, especially those showing seasonal changes in climate.

79. In studying the effects of a major nuclear exchange upon weather and climate, the models must be able to simulate not only the (known) normal climate but also the (unknown) perturbed climate that would result from an unprecedented loading of the atmosphere with large amounts of particulate material. For all the uncertainties, the numerical models of the atmosphere constitute the most powerful tool available. They may be used to estimate the direct atmospheric effects of a major nuclear war. They are the only means by which unforeseen interactions or feedback effects can be explored. Most of the findings described below are based on the results of numerical simulations with various kinds of climate models.

80. The climatic effects of nuclear war are studied by specifying the distribution of smoke, soot and dust that would be injected into the atmosphere by nuclear detonations and subsequent fires, and introducing into the computations the optical properties of these materials as well as additional mathematical equations to account for the transport, transformation and eventual removal of smoke by the atmospheric processes.

81. By introducing into the computations the optical effects of smoke, soot and dust emitted by fires ignited by nuclear detonations, the general circulation models have been adapted to study the possible effects of nuclear war on the climate. Given that climate modelling has both great strengths and weaknesses, that there is a tendency for some to extrapolate predictions further in time than is warranted by the knowledge of relevant processes, or to quote model results in too literal a fashion without consideration of the caveats concerning the limitations, it is no surprise that the applications of models to a subject as novel and controversial as the so-called "nuclear winter" hypothesis have been contentious. The primary value of model simulations lies in their role as investigative tools, essential to the processes by which science tests, and thereby advances, its understanding of climate. Again, as Schneider (1987) says:

> "Mathematical climate models cannot simulate the full complexity of reality. They can, however, reveal the logical consequences of plausible assumptions about the climate ... Climate models do not yield definitive forecasts of what the future will bring; they provide only a dirty crystal ball in which a range of plausible fortunes can be glimpsed. They thereby pose a dilemma: we are forced to decide on how long to keep cleaning the glass before acting on what we think we see inside."

Models may therefore be used:

(a) To explore options and reduce many unknown factors to a few that are amenable to further investigation;

(b) To differentiate between assumptions that are weak and those that are robust;

(c) To test the climate's sensitivity to changes in key variables and establish boundary conditions;

(d) To improve the quality of decision-making. This may mean identifying the courses of action that minimize negative consequences and assist in avoiding the worst decisions.

10. Results of numerical simulations

82. The one-dimensional calculations by the TTAPS group (Turco et al., 1983) provided a preliminary indication that the climatic effects could be significant. These were quickly followed by two-dimensional (MacCracken, 1983) and three-dimensional calculations (Aleksandrov and Stenchikov, 1983 and 1984; Covey et al., 1984). Since these early studies, progress has been made in estimating the potential perturbation to the atmosphere induced by smoke over the first several weeks following a nuclear war. The early calculations typically assumed fixed smoke extent and quantity, but ignored scavenging and smoke transport, and considered only the absorption of solar radiation, while neglecting scattering and the effects of the particles on the thermal infra-red (long-wave) radiation. The most recent calculations have attempted to correct these initial simplifications.

83. These new calculations were performed both in the United States and the USSR (Malone et al., 1986; Ghan et al., 1987, 1988; Thompson et al., 1987; Stenchikov and Carl, 1988). All models have different vertical and horizontal resolutions, but the results for a first month after the injection are quite similar (Golitsyn and MacCracken, 1987). The models show a rapid decrease in the surface temperature, much like a prolonged night-time cooling. Under dense smoke clouds inside continents the temperature drop could be 20 C to 30 C during the first days in warmer months of the year, producing occasional occurrences of sub-freezing conditions (Golitsyn and MacCracken, 1987). During the first two weeks the northern hemisphere mean land surface temperature in mid-latitudes would decrease by 15 C to 20 C.

84. As smoke spreads southwards and is subject to removal, the temperature changes begin to be moderated, producing mean changes of the order of 5 C to 10 C in the sub-tropics and the tropics, with the chance of some occurrences below 15 C, which is an important threshold for rice production. Changes in precipitation would be much more drastic and significant, especially in lower latitudes, because of the warming of the atmosphere and cooling of the surface. This would be so even for smaller amounts of smoke. Recent numerical simulations at the Lawrence Livermore National Laboratory (reported by MacCracken at the Moscow SCOPE-ENUWAR workshop, 21-25 March 1988) showed that the precipitation in middle and low latitudes of the northern hemisphere averaged over land was reduced by a factor of 5 during the first weeks.

85. Other important general conclusions of the models include the suppression of the summer monsoons even for the initial moderate amounts of smoke. The models with high vertical resolution (Malone et al., 1986; Covey, 1987) show that during the warm part of the year the smoke heated in its upper parts would reach altitudes of 25-30 kilometres. At these heights it would stay many months or even years. According to Malone et al. (1987), about one third to one half of the smoke could reach the stratosphere for a representative case.

11. Partial, natural analogues for atmospheric disturbance caused by nuclear detonations

86. There have been a number of efforts to analyse various natural phenomena to determine whether, and to what extent, the injection of particles (dust, smoke, etc.) can affect surface temperature. These analyses may provide partial analogues for the effects of smoke from nuclear fires and may also be used for partially validating the model simulation of the climatic impact of a nuclear exchange. The use of natural phenomena in this manner has not revealed any inconsistencies in the predictions based on numerical simulations with atmospheric models. Smoke and dust from, for example, volcanic eruptions and large forest fires differ in many ways from those produced by nuclear explosions and urban fires, but may be useful for giving physical insights into the problem (Golitsyn and MacCracken, 1987).

87. Martian dust storms demonstrate that intense heating of the atmosphere and intense cooling at the surface occur (Turco et al., 1983; Golitsyn and Phillips, 1986). Terrestrial dust storms also provide some insight. A temperature decrease

of several degrees was reported in Nigeria following a Saharan dust storm (Brinkman and McGregor, 1983); a rapid drop of 10 C has been observed after the arrival of an intense dust storm in north-western China (Xu et al., 1979); and during about 50 dust storms and heavy dust hazes 5 meteorological stations in Tadjikistan showed an average cooling of up to 10 C to 12 C during the daytime (Golitsyn and Shukurov, 1987). Further, millions of tonnes of dust from Saharan dust storms can be transported for considerable distances. There is a correlation between dust hazes and crop yield: the longer the period of haze, the less the yield (Golitsyn and Shukurov, 1987).

88. Major forest fires also provide natural analogues. Siberian fires of 1915 generated 30 ± 10 million tonnes of smoke over a period of about 50 days (Golitsyn, 1987; Veltishchev et al., 1988), which caused a temperature decrease of several degrees at a number of Siberian stations. The large forest fires in the eastern Soviet Union in 1972 resulted in a decrease in surface sunlight by a factor of 2 or more (Abakoumova et al., 1986; Sokolik et al., 1986). Smoke from fires in California in 1987 was trapped in valleys and produced a decrease of daytime maximum temperature more than 15 C below normal for a week (Robock, 1988). Moreover, smoke from forest fires can be transported to remote regions. For instance, that emitted by a big forest fire in China in 1987 passed over Alaska (Robock, 1988) and smoke from the Alberta fire of 1950 crossed Canada, the United States and the Atlantic and reached western Europe. These events were associated with a drop in daytime temperature in north America of several degrees Celsius (NRC, 1985).

89. The impact of nuclear war on climate, in the chronic phase, lasting a month to perhaps a few years after the war, can be inferred in part from the effects of major volcanic eruptions, which inject large amounts of particulate matter into the stratosphere. The giant eruptions of the Indonesian volcanoes of Tambora in 1815 and Krakatoa in 1883 caused a temperature depression at the Earth's surface of about 1 C (NRC, 1975). Studies on the influence of other volcanic eruptions on climate are fairly numerous, but definite conclusions are difficult to make because single eruptions are seldom large enough to produce a significant change in global climate. Nevertheless, regional effects appear to be correlated with such events. This was demonstrated in 1816 (the "Year Without a Summer"), following the eruption of Tambora, when many crops failed in Europe and North America. A recent study has considered 36 cold events in China over the past 500 years, of which 32 appeared to have followed volcanic eruptions.

90. Clearly, dust and smoke aerosols can influence surface temperature and be used to validate global and regional models. Their use has not revealed any inconsistencies in the predictions made using computer simulation models, and can therefore be regarded as partial analogues for the smoke produced by nuclear detonations. Smoke and dust from these natural events differ in many important ways from that produced by nuclear-induced fires and consideration of a wider range of analogues may be useful for giving further insights into the problem (Golitsyn and MacCracken, 1987).

12. Long-term effects

91. A climatic perturbation lasting a year or so after the nuclear exchange and causing a decrease in temperature several degrees below normal would pose an additional threat to natural and managed ecosystems that may have survived more severe, but transient, effects during the first weeks.

92. The intense warming of the upper part of the smoke cloud by solar radiation could produce strong vertical motions of the atmosphere and hence loft smoke into the stratosphere from where it could rapidly spread southward (Malone et al., 1986). This lofted smoke would be added to that which had been directly injected into the stratosphere by the most intense fire plumes (Cotton, 1985) and smaller-scale convection processes (Demchenko and Ginsburg, 1986) adding to the total amount of smoke in the stratosphere (Malone et al., 1986; Ghan et al., 1987 a). For large smoke injections, it is estimated that up to about one half of the initial mass of smoke would remain in the atmosphere after one month, almost all of it above the level where it could be scavenged by precipitation.

93. Similarly, the reduction of solar radiation reaching the surface could initially cause a hemispherically averaged cooling of the ocean upper mixed-layer of the order of 1 C per month. This rate of cooling would decrease as the amount of smoke diminished but could result in a cooling of the ocean upper layer by several degrees Celsius over a year. The cooling would be stronger in the northern hemisphere where the smoke would be thick. The changes in ocean and air temperatures would also allow an earlier formation of sea ice, an effect first studied in this context by Robock (1984) using an energy balance climate model, and more recently examined in general circulation model calculations by Covey (1987), Ganopolsky and Stenchikov (1987) and Ghan et al. (1987 b). These studies indicate that the earlier formation of sea ice could result in a prolonged cooling of northern hemisphere land areas by a few degrees and could last through at least the first warm season following a spring or summer nuclear war.

C. Uncertainties

94. There are two types of uncertainty. One originates from the nature of a nuclear exchange and is in essence the problem of targeting strategy and the conduct of a nuclear war. This includes the adversaries, choice of targets, timing (season) of the war, total explosive yield of the weapons, types, sizes and numbers of different warheads used, the height of the burst (ground, near ground or air bursts) and many other such factors.

95. The second type of uncertainty is of a scientific nature, i.e. insufficient knowledge of the physical processes governing the generation, injection and evolution of aerosols and the dynamics of atmospheric circulation on all relevant scales of motion, as well as the limited ability of numerical models to describe exactly the behaviour of the atmosphere, especially in the perturbed conditions following a major nuclear war. It is important to recognize that the uncertainties, when resolved, might act to reduce or to increase the effects.

96. The combination of all these uncertainties does not, however, impair the validity of the main conclusion of the scientific studies according to which the risk of a significant global climatic perturbation resulting from a major nuclear exchange involving the large urban and industrial centres and taking place in the northern hemisphere summer is beyond doubt.

D. Destruction of stratospheric ozone

97. By absorbing ultraviolet solar radiation, the ozone layer is a heat source for the stratosphere, thus maintaining the tropopause. Consequently, any major changes in the ozone layer would have an effect on the general circulation of the atmosphere with implications for the climate and weather.

98. The stratospheric ozone layer is extremely important for life on Earth. It shields the Earth's surface from much of the ultraviolet radiation that is harmful to many living organisms (UV-B). For example, elevated levels of UV-B may cause harm to many plants, particularly those in aquatic ecosystems, and may depress the human immune response and lead to increased incidence of skin cancer. Many plants and animals have evolved or adapted to relatively constant UV-B levels and would suffer from increased levels of UV-B if the ozone layer were seriously depleted.

99. The high temperatures generated by a nuclear fireball cause the dissociation of diatomic oxygen and nitrogen. As the incandescent gases cool as they rise through the atmosphere, the oxygen and nitrogen atoms combine and a number of different oxides of nitrogen are formed. A 1-megaton nuclear burst is at present estimated to produce about 5,000 tonnes of these nitrogen oxides.

100. Of particular importance is nitrogen dioxide, which can absorb sunlight in a spectral range from ultraviolet to green. Calculations carried out in the USSR (Izrael, 1984; Kondratyev et al., 1985) suggest that this could, by itself, produce a cooling of several degrees Celsius, but the effect has not yet been incorporated in any detailed, comprehensive simulations.

101. Nitrogen oxide molecules produced in the fireball enter into a series of chemical reactions with ozone in which the nitrogen oxide behaves as a catalyst, causing two ozone molecules to break down and form three oxygen molecules. This reaction is slow, so that the ozone content of the stratosphere would reach a minimum after several months to a year, with a recovery to normal levels after two to three years. The amplitude of the decrease would depend upon the total explosive yield, the height of the detonations and many other factors. Global reductions of up to about 50 per cent were predicted in the 1970s when nuclear arsenals consisted mostly of hydrogen bombs with yields in the megaton range. Because the present arsenals consist mostly of smaller warheads in the kiloton and low megaton range, it had been thought that their use might limit the extent of ozone destruction.

102. However, the heating of the stratosphere caused by the presence of elevated smoke would increase the rate of ozone destruction, introducing again the estimate that about half the ozone may be destroyed (Vupputuri, 1986). The ozone could also

react with the soot on a timescale of a year or more (Stephens *et al.*, 1988). In this process both soot and ozone would be destroyed. Moreover, the atmospheric motions might be very important in determining the integrity of the ozone layer, for example, preliminary calculations suggest that vertical motions would move large quantities of tropospheric air, containing little ozone, into the stratosphere where high ozone concentrations could be diluted. As a consequence, reductions of ozone exceeding 50 per cent might be expected. Further studies are urgently needed because of the potential importance of this process.

E. Other chemical effects

103. The additional absorption in the visible solar spectrum by nitrogen dioxide would also reduce the proportion of photosynthetically active radiation, which is essential for the photosynthetic activity of autotrophic plants on which most ecosystems, and all agriculture and fisheries, depend.

104. Although more research is needed to quantify the effects of nitrogen oxides on the spectrum of solar radiation reaching the surface, the possibility of increased levels of UV-B coupled to a decrease in the amount of photosynthetically active radiation suggests *prima facie* that there might be severe consequences to the biosphere from the injection of nitrogen oxides into the upper atmosphere.

105. A number of other harmful chemical agents could be released by fires following the destruction of chemical plants and other industrial installations. These, which include carbon monoxide, asbestos and a large range of pyrotoxins, have recently been reviewed by Birks and Stephens (1986) and by WHO in a recent report (1987), but systematic research on the subject is only just beginning.

III. EFFECTS ON NATURAL ECOSYSTEMS AND AGRICULTURE

A. Introduction

106. Harwell and Hutchinson (1986) argued that the direct destruction of social infrastructure in a major nuclear war, coupled with a change in climate, could lead to unprecedented famine on a wide scale. Trying to estimate how societies might respond to famine, epidemic disease, impairment of economic productivity and collapse of trade - perhaps on a global scale - can only be attempted in the most general terms. Two world wars in this century have caused terrible loss of life and major geopolitical, economic and social revolutions, but these offer limited precedent for the aftermath of a nuclear war because earlier conflicts have not taken place in a context of global agricultural and ecological collapse.

107. The SCOPE-ENUWAR study paid particular attention to the likely direct effects of the climatic anomaly on plants, whose photosynthetic activity forms the basis of all but a few exceptional ecological systems. The study also investigated the impacts on specific and important species, ecosystems and biomes. There are many indirect and subtle processes that are of immense importance in the integrity of the ecosystem: interactions between species, including mutualisms, competition between species for resources, predation, parasitism and disease.

108. It also summarized the impacts to the biosphere and made a number of general conclusions that are reiterated here in brief:

(a) The type of climatic alterations that have been proposed in the aftermath of a large-scale nuclear war could cause severe, widespread and unprecedented harm to global ecological and agricultural systems;

(b) Terrestrial ecosystems would be most harmed by severe and rapid changes in temperature and by precipitation, aquatic ecosystems by a diminution of sunlight (insolation). A long-lasting decrease in precipitation could have a severe impact on terrestrial and freshwater ecosystems;

(c) The ultimate effects of a climatic change would depend on the season in which the war occurred. Temperate ecosystems would be most strongly affected by a spring-summer war, less so by a winter conflict. Tropical ecosystems would be at hazard from any appreciable climatic anomaly;

(d) The vulnerability of a species varies greatly through its life cycle;

(e) Global delayed radiation fall-out would not constitute a particular hazard to ecosystems. Local fall-out immediately following a nuclear attack may be lethal to particularly sensitive plants and animals;

(f) Even if radioactive fall-out does not cause appreciable direct harm to aquatic and terrestrial ecosystems, there may be significant accumulation of radionuclides through the food chain leading to harmful, internal doses to the exposed human population;

(g) Depletion of the stratospheric ozone layer by pollutants injected into the atmosphere may lead to an increase in biologically active ultraviolet radiation (UV-B) to harmful levels over large geographical areas;

(h) The widespread dissemination of toxic substances, particularly by air, rivers and streams, could result in contamination of estuarine and coastal food chains, possibly leading to dangerous exposure for humans;

(i) Fire would destroy large areas of forest in the vicinity of military targets. If there was a major drop in precipitation with concomitant increase in fire hazard, there could be significant destruction of forests.

109. Clearly, many ecosystems would be exposed to more than one of these stresses. It is possible that some impacts may counterbalance or negate each other but more likely that impacts would be synergistic and exacerbate each other's effects:

(a) The loss of crops in the period immediately following the nuclear exchange may limit the availability of seeds for replanting, particularly specialized hybrids; depressed productivity in the chronic phase could further reduce seed availability; crop failures would mean that valuable seeds had been wasted; seed stocks would be consumed directly as food, limiting supplies for replanting; hybrid cultivars appropriate to particular environmental conditions would not be readily available;

(b) The loss of experienced farmers through incapacitation or death would limit the base of experienced knowledge essential for efficient agriculture and minimizing the risks of crop failure;

(c) Soil productivity could be reduced through the impact of fires, erosion resulting from the loss of vegetative cover and changes in hydrological régime, nutrient leaching, contamination by radio-nuclides and toxic materials, poor conservation practices caused by lack of farming experience or the need to extract maximum productivity over a short period of time;

(d) Enhanced levels of ultraviolet radiation caused by depletion of the ozone layer could harm crops. If the ozone layer were depleted to any appreciable extent it would be slow to recover. In such a case, UV-B levels could be increased over a long period, even if that increase were small;

(e) Agricultural and ecological changes following nuclear war could increase both pests and weeds at a time when pesticides and herbicides would be relatively unavailable;

(f) Agricultural machinery and technology, including service and spare parts would not be available;

(g) Draft animals would assume increasing importance in agricultural technology but might be in reduced supply because it would take time to replace those which were casualties; many could not be fed and many would have been eaten in the acute period of food shortages. Those which were available would not be properly distributed and breeding stocks would be lost;

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(h) A dispossessed urban populace could migrate to rural areas in search of food, damaging crops in the process.

B. General biological responses to climatic perturbations

110. Large seasonal variations in temperature and light prevail at high latitudes where many plants and animals possess physiological and behavioural mechanisms that enable them to survive periods of low light and to resist the effects of chilling and freezing.

111. If a nuclear war occurred in winter, the biota at temperate and northern latitudes might be able to resist a climatic perturbation. In spring or summer, temperate plants might be as vulnerable as low latitude species because seasonal acclimation and hardening cannot be triggered instantaneously.

112. Biological production results from the photosynthetic activity of green plants. This is dependent, among other factors, on solar illumination and would therefore be impaired by any prolonged reduction in the amount and effectiveness of light reaching the Earth's surface.

113. Animals may show various adaptations that enable them to cope with seasonal temperature extremes, such as seasonal acclimation, hibernation or adjustments to the internal biological clock that may be partly independent of the external environment. However, an unseasonal drop in temperature and reduction in solar illumination could cause significant shock and might even, for some species, be disastrous. Pregnant and young animals and migratory species would be particularly susceptible.

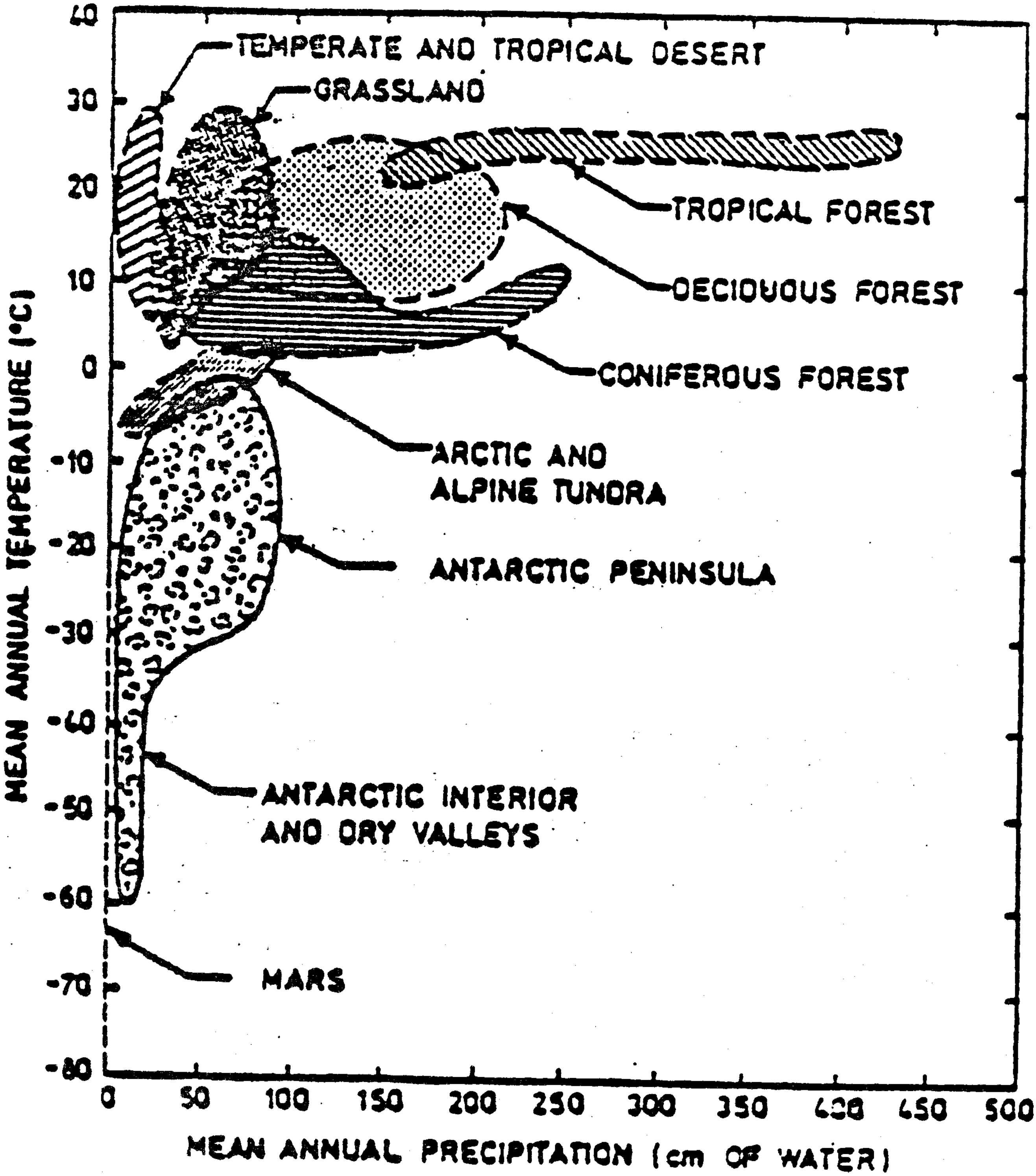
C. Responses of biomes to climatic perturbation

114. Plants and animals experience and tolerate considerable, but not unlimited, variability in their environment. From examination of ecosystems on a global scale it becomes evident that terrestrial plants, and with them animals, exist as reasonably well-delineated biomes (figure 2) whose distribution can largely be defined in terms of mean annual temperature and precipitation.

115. Simulation of the normal functioning of ecosystems and their responses to perturbations presents problems that are comparable in complexity with that of simulation of climate and weather. At present generic models are available for few natural or managed ecosystems. A number of models have been used to simulate the productivity of various ecosystems, notably grasslands and forests, under a variety of proposed climatic scenarios that might follow a nuclear war (Harwell, 1984).

116. The SCOPE-ENUWAR group undertook an extensive assessment of the ecological and agricultural impacts of expected climatic perturbation and concluded that the limited ability of low latitude terrestrial ecosystems to tolerate environmental variability makes them extremely vulnerable. This has major implications because it emphasizes the biological fact that the potential for disaster is not simply a consequence of the amplitude of the temperature drop, reduction in insolation or

Figure 2. Terrestrial biomes in relation to mean annual temperature and precipitation



Source: M. A. Harwell and T. C. Hutchinson, Environmental Consequences of Nuclear War, vol. II (Chichester, 1985), p. 62.

change in precipitation, but is defined by the ability of different biomes to withstand the stresses.

117. The appearance of gaps in the forest canopy over large areas, elevated levels of ultraviolet radiation, contamination by radioactive isotopes and other toxic substances, acid precipitation and outbreaks of pest and weed species might also lead to further degradation of the forests of northern Europe and North America. Recovery would be very slow and dependent upon the amount of soil erosion and waterlogging (Svirezhev et al., 1985).

1. Tundra/alpine biomes

118. The Arctic biomes of the tundra, north of a latitude of 65° N, withstand extremely low temperatures down to -50 C (and occasionally -70 C) in the normal winter. Provided they have undergone the normal cold-hardening period and have entered dormancy, they would be relatively immune to an additional drop in temperature and reduction in sunlight such as that anticipated after a nuclear war, even if cold weather persisted into the following summer. The behaviour of alpine systems would be similar.

119. A very different situation would prevail following a summer attack. Growing plants would probably be harmed or killed by the rapid onset of sub-zero temperatures. Some might undergo a premature winter cold acclimation and this, in conjunction with the large seed banks that typify many arctic and boreal species, could enable them to regenerate.

120. Herbivorous, non-hibernating animals that are dependent upon browse and birds would be the principal casualties and high mortality could be expected.

2. Boreal forest/taiga

121. Nuclear war in the northern hemisphere would place ecosystems below the tree line, such as the taiga, boreal forests and temperate mixed forests, under stress. Like arctic plants, many would survive climatic perturbation following a winter war if they were already cold-hardened and standing dormant. More southerly forms, such as pines, many shrubs and herbaceous species, could be killed by cold. The SCOPE-ENUWAR study estimated that the mortality could be as great as 25-75 per cent. The freeze-resistant seed banks characteristic of mid-latitude plants would facilitate recovery if the climatic anomaly did not persist too long.

122. Climatic consequences of summer war would cause massive destruction of the major plant species. Recovery would be further impeded if there was a shortening of the growing season in subsequent years sufficient to reduce productivity. The accumulation of a large quantity of dead wood and litter might increase the vulnerability to fire and to insect pests, raising the possibility of a second-order of devastation in the chronic period following the war. Of greater significance is that the forests would take decades to resume their full productivity and might undergo a major change in species composition such that the original ecosystem might never regenerate.

3. Coniferous forest

123. Coniferous trees are particularly sensitive to ionizing radiation and 20-30 per cent of the forests of the northern hemisphere could die as a result of the direct impact of nuclear explosions and subsequent fires. In a winter war, approximately 80-90 per cent of all trees might survive a year of abnormally low temperature. In a summer war, the fall in illumination and temperature would kill most trees. Seeds capable of germinating would be preserved in the soil in both cases.

4. Deciduous forest

124. A summer war would have a severe impact on the deciduous forests of the northern hemisphere with most of the trees being killed. A winter war would cause partial damage. Recovery would depend mainly on vegetative reproductive organs rather than seeds and the rate of recovery could depend on the degree of soil erosion. It has been estimated that in 50 years damaged deciduous forest would recover about 70 per cent of its original biomass (Svirezhev et al., 1985).

5. Grasslands

125. The steppes and prairies of the temperate northern hemisphere would be vulnerable, especially to a summer war that would cause devastation to the plants and dependent animal life (soil organisms, grazers, dependent predators and birds). Grasslands would recover relatively quickly on the return of a normal climatic régime, owing to their rapid regeneration time compared to that of forests.

6. Deserts and semi-deserts

126. Like other ecosystems at comparable latitudes, the cool semi-deserts of the northern hemisphere would withstand the climatic effects of a winter conflict. The hot deserts do not have such pre-adaptation to low temperatures and their diverse flora and fauna would suffer considerable harm. A summer conflict that gave rise to low insolation and low temperatures would cause devastation at all latitudes.

7. Tropical biomes

127. Though occupying only 11 per cent of the earth's land surface, tropical rainforests support 32 per cent of the net primary production, 42 per cent of the plant biomass and 33 per cent of the animal biomass and account for much of the species diversity of both plants and animals (Harwell and Hutchinson, 1986). These forests are adapted to higher levels of temperature, light and precipitation. Severe cold for even short periods (the temperature would not have to reach freezing) would be disastrous for the plants and their dependent organisms. Occasional incursions of polar air into the Amazon basin under present conditions cause extensive damage to the rain forest. Regeneration of damaged tropical rain

forests could be limited by loss of fertility and the complexity of reproductive mechanisms.

128. Deciduous forests would be especially vulnerable during the wet season, which is one of active growth. The tropical grasslands and savannahs would be more vulnerable to low temperatures and rainfall than their temperate counterparts, prairie and steppe. A reduction in the summer monsoons would have a large effect on these ecosystems.

129. Similarly vulnerable are the mangrove swamps that fringe many subtropical and tropical coasts. Mangroves are unique ecosystems that harbour a wide variety of ecologically and economically important species. Even a modest reduction in temperature that might follow a nuclear war could cause widespread destruction at any season of the year.

8. Lakes and streams

130. The impact on freshwater ecosystems would depend upon the severity of the cooling, the level to which illumination were to fall and changes in precipitation. The size of the water bodies would determine their ability to buffer changes in temperature.

131. Even for a winter war, when northern lakes are frozen, the thickness of the ice might be increased such that the water would freeze to the bottom of shallow lakes killing fishes and other animals. Any extension of winter conditions, or a summer war, could disrupt the normal cycle of development, growth maturation and breeding of aquatic organisms.

9. Marine systems

132. The oceans cover 71 per cent of the Earth's surface and support a significant proportion of the planet's biological productivity. Their large volume and thermal inertia make them relatively immune to short-term changes in temperature. Reduction in sunlight and changes in the radiative spectrum would depress photosynthesis and the primary productivity of the phytoplankton in the surface layers. This would affect dependent food chains but it is not expected that there would be a permanent loss of any key organisms or damage to important fisheries. The severe impact on fisheries and marine ecosystems that resulted from the changes in sea temperature that characterized the El Niño phenomenon in 1983 off the Pacific coast of South America must surely discourage complacency about the climatic effects on ocean food chains.

133. The most productive marine ecosystems, from the point of view of human consumption, are those of the continental shelves. The relatively shallow waters would be more sensitive to temperature fluctuations. There could also be changes in water quality resulting from variations in fresh water discharge by rivers, sediment transport and nutrient inputs. Increased loadings with radio-nuclides and toxic materials would also be likely results of a major nuclear war.

134. In tropical and subtropical regions, the shallow water flora and fauna, especially coral reefs, would be vulnerable to temperature fluctuations and fall in illumination. They would be adversely affected by heavy burdens of suspended sediment and water-borne pollutants.

10. Estuaries

135. Estuaries and their associated wetlands, which have characteristically high biological productivity and are often of great importance for human subsistence and economy, would also be greatly affected by changes on the land. Destruction of terrestrial systems would cause soil erosion, elevating the burdens of suspended material and dissolved substances (many of them toxic) in rivers and ultimately in the estuaries. This effect might be increased by climatic perturbation and could devastate estuarine fisheries.

D. Response of major agricultural systems to climatic perturbations

136. The human population of the Earth exceeded 5 billion (5,000 million) in 1987 and at the current projected rate of growth this figure will double in approximately 40 years, with an additional billion (1,000 million) persons being added within 11 years. The subsistence of this population is based almost wholly on agriculture.

137. Even the less extreme scenarios for climatic change following a major nuclear war would entail global agricultural perturbations for which there is no historical precedent (Harwell and Hutchinson, 1986). Some of the most severe climatic effects have been associated with changes in annual mean temperature that are small in comparison to those which might result from a major nuclear war. For example:

	Approximate temperature changes (Degrees Celsius)
Holocene warming (recovery from the last Ice Age), 8000-4000 BP	+5
Little Ice Ages, 17th and 19th centuries	-1 to -2
Variation over past 100 years, (northern hemisphere)	±1
Year Without A Summer, 1816 AD (northern hemisphere)	less than -5

138. The SCOPE-ENUWAR study has undertaken the most comprehensive analysis of the post-nuclear war climatic impact on agriculture, assuming the following climatic scenarios (Harwell and Hutchinson, 1986):

(a) Acute phase (temperature): short-term depression in average temperature to freezing or sub-zero levels coupled with a reduction in sunlight to 1-10 per cent of normal levels;

(b) Chronic phase (temperature): long-term reductions in average temperature to several degrees below normal coupled with reductions in sunlight to 80-95 per cent of normal levels;

(c) Acute/chronic phase (precipitation): reduction in precipitation to 50 per cent or less of normal annual average.

139. The vulnerability of global agricultural systems and specific key crops was evaluated against these scenarios. The method of assessment varied, using evidence from historical case-studies, statistical inference, physiological inference and analytical or numerical models. The study also considered the possible losses of manpower, energy, fertilizer and other subsidies in the post-war environment.

140. While the cumulative effects of a change in temperature are undoubtedly important, crops (and natural ecosystems) are mainly sensitive to short-term variations. The yield of a crop is determined in part by the length of the growing season and by the effects of temperature and/or rainfall.

141. From a review of a number of studies and their own analysis of climate data, the SCOPE-ENUWAR group concluded that, for mid-latitudes, a fall of 1 C in average temperature was equivalent to a shortening of the frost-free growing season by 10 or 12 days (Harwell and Hutchinson, 1986). Many temperate zone crops are grown close to the limit of their growing season and it is clear that a temperature drop in the order of 5 C-10 C for weeks or months would eliminate the yield.

142. It is difficult to predict the variability in weather that can result from a change in climate, for example, the probability, intensity and duration of cold episodes. Some historical evidence supports the notion that abnormally cool years also show a disproportionately high variability and incidence of cold episodes and that this correlates with crop failures. This non-linear relationship between mean values and variability is also supported by the examples of the killing frosts that devastated agriculture in North America and Europe in 1816, and the severe 1983 El Niño. These are both examples of extreme climatic variability that correlate with average global temperature changes in the order of at the most -2 C in the former, and less than -1 C in the latter case (Harwell and Hutchinson, 1986).

143. There is also a parallel with respect to precipitation. Areas receiving high precipitation have the lowest variability (departures from the annual average of 10-20 per cent), while arid regions show greater variability (departures from the annual average of more than 30 per cent). Given that the former include the most productive agricultural land of North America, Europe and Asia, a fall of 25-50 per cent in precipitation coupled with the resulting increase in variability could jeopardize agricultural production and with it the subsistence base of many people.

144. With respect to the acute phase, the SCOPE-ENUWAR group (Harwell and Hutchinson, 1986) concluded that the most extreme stresses (predicted from the climate models) have no precedent in history and their impact cannot be predicted from statistical models of agricultural production. Insight can only be gained by extrapolation from what is known about the physiology of plants. In the case of less extreme climatic perturbations in the acute phase and in the chronic phase:

(a) Reductions in average temperature would slow the rate of crop development;

(b) Even if the temperature reduction in the growing period were small, late frosts in the spring and early frosts in the autumn could damage plants or shorten the growing season below the critical threshold for maturation;

(c) Reduction in average temperature could be compensated by a lengthening of the growing season. Under the climatic scenarios this is not probable, particularly in temperate and subtropical regions;

(d) Physiological thresholds exist for the survival of a plant and for its ability to mature and produce a crop. The impact of any temperature reduction must be assessed against these thresholds. For example, a given fall in temperature to a minimum that lies above the threshold may have only a slight effect on growth and yield. A similar fall, but one that goes below the threshold, may prevent maturation and hence loss of the crop;

(e) Climate models predict major changes (usually reductions) in precipitation with potentially disastrous effects (droughts).

E. Major food crops

1. Rice

145. Rice is a major food staple of the world and plays a significant role in the economies of several developing countries. About 3 billion (3 thousand million) people eat rice daily and about 300 million farmers grow it in a wide range of systems (irrigated, rainfed upland, rainfed lowland, deepwater, tidal wetlands). About 50 per cent of the world's rice is grown as a rainfed crop.

146. The crop is grown under a wide range of climatic conditions in areas spanning latitudes of 40° S in central Argentina to 53° N in north-east China and from just below mean sea level in southern India to more than 2,000 metres above mean sea level in the sub-Himalayan region. Seasonal and spatial variations in climate affect rice productivity. Temperature, solar radiation and rainfall are important factors that directly influence rice yields and also indirectly through their effects on disease and insect pressure (Seshu et al., 1987). In temperate regions, the rice calendar is circumscribed by the temperature régime and in the tropics primarily by precipitation, determined by the dates of onset and withdrawal of the monsoon. The critical low and high temperatures vary in relation to the growth stages and are generally below 15 C and above 35 C. Too little or too much rainfall at any growth stage can cause partial or total crop failure. Solar radiation has the greatest effect on grain yield in the reproductive and ripening stages.

147. Rice is less tolerant of low temperatures than most other grain crops. Data from rice cultivation in Japan suggest that periodic excursions of temperature to below 15 C at critical stages of development could reduce the yield by about one third and a drop in average temperature of 1 C-2 C over the growing season would be sufficient to eliminate the yield (Harwell and Hutchinson, 1986). These authors concluded that in the acute phase following a nuclear war "rice production would essentially be eliminated in at least the northern hemisphere, and the southern hemisphere could experience the same fate".

148. In the chronic phase there could also be substantial loss of the crop. Depending upon the region and variety of rice grown, the critical temperature range for Japan is 19.0 C-25.5 C and yields would be reduced if temperatures fell below this, even if there were no short-term, low temperature episodes or other perturbations. A simulation model run for the north of Japan indicated that a 2 C average temperature drop in the growing season would reduce the rice yield by 70 per cent.

149. More recent climate models indicate the possibility of a large reduction in monsoon rainfall in both the acute and chronic phases following a nuclear war. Irrigated crops are sensitive to variations in water supply and reductions in precipitation could be very serious. For rainfed rice (paddy and upland), which is grown on approximately 50 per cent of the world's rice area, the situation could be disastrous. Acute water stress could seriously affect production and also reduce the area suitable for rainfed culture. This would have serious socio-economic consequences because the poorer sector of rice farmers in developing countries subsist on rainfed rice.

2. Wheat

150. Winter wheat would survive air temperatures down to -50 C if insulated by snow. However, even a small average temperature decrease or shortening of the growing period could severely limit crop yields in many of the major northern production areas. Most of the crop of Canada, the United States, western Europe, the USSR and China would fail. A war in the middle or late northern hemisphere summer might permit a harvest in India, China, north Africa and the United States, probably not in Canada, western Europe and the USSR. The growing period necessary for maturation of the crop would be lengthened in the southern hemisphere (Australia, South America, southern Africa).

3. Maize

151. The maize crop of Canada, the United States, Europe, the USSR and China would be extremely susceptible to short cold spells and could fail. Maize is grown close to its limits for water availability and would be extremely vulnerable to any reduction in precipitation, particularly in central Africa and Central and South America. For a northern hemisphere summer war, the growing season for maturation of the crop would be lengthened in the southern hemisphere (Australia, South America, southern Africa).

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4. Soybean

152. Soybeans in the northern temperate regions would fail because of the cold temperature and reduced light levels in the event of a summer war. Provided there was adequate rainfall, soybeans grown at lower latitudes of the temperate zone would survive a winter war.

5. Livestock

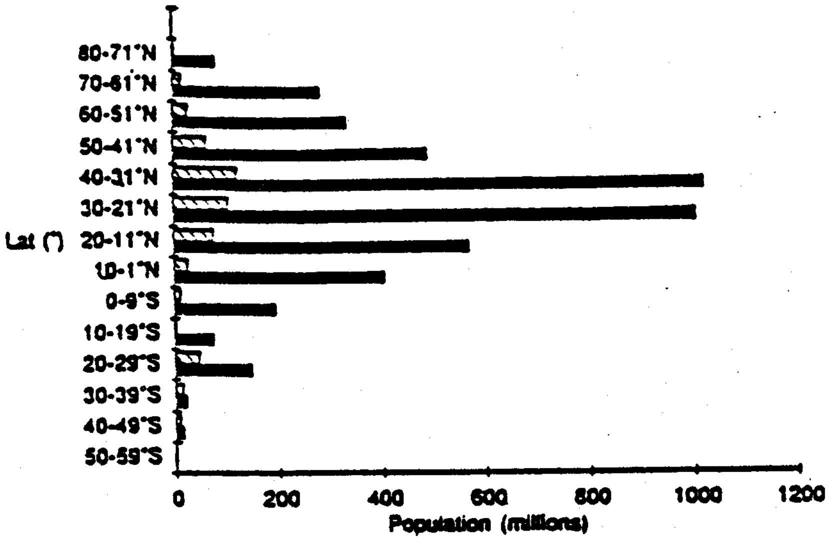
153. In the event of a winter war in the northern temperate zone, intensively housed animals would not survive the failure of heating, feeding, ventilation and other support services. Young animals would suffer cold stress, adult ruminants would survive the cold but be vulnerable to shortage of water and fodder. Food availability would be the principal stress on tropical livestock. In the southern hemisphere most livestock would survive but be vulnerable to shortage of fodder. Low light levels might interfere with the fertility of sheep.

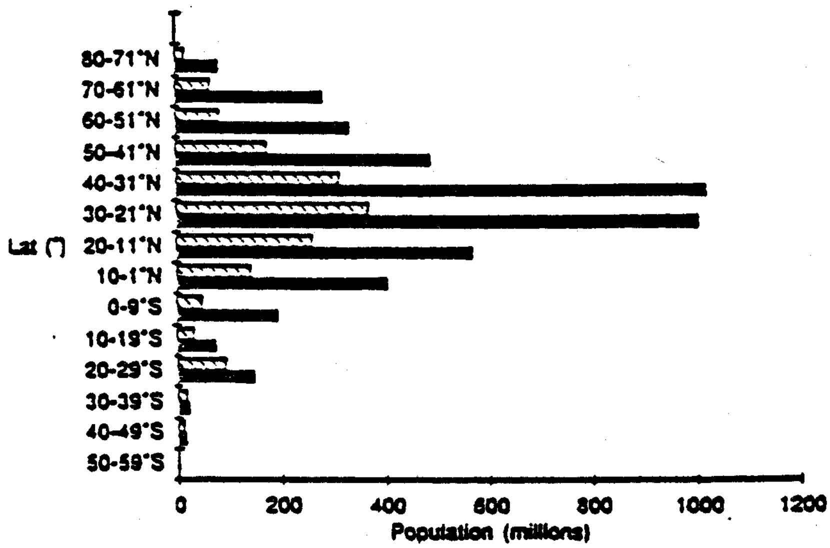
F. Implications of climatic perturbation by latitude

154. Obviously, the level of climatic perturbation induced by nuclear war and the associated impact on food production will vary with hemisphere and with latitude. These effects have been summarized by Harwell and Hutchinson (1986) and are shown in figure 3, where the vulnerability of a major part of the world's population to loss of food supply is made clear.

155. The timing of the nuclear exchange and its impact on existing crops has been considered in relation to seasonal variation in food stocks. The relatively low levels of food stocks available in most latitude zones would limit the ability to cope with the loss of current food crops. This is demonstrated in figure 3 by a comparison between surviving population if nuclear war takes place when food stocks are (a) at a minimum and (b) at median levels.

Figure 3. Vulnerability of human population to loss of food





Note. The solid bars indicate current population, striped bars the survivors. The upper plot shows the impact of a loss of food production when stocks are at a minimum, the lower plots show the effect when food stocks are at a median level. The calculation is sensitive to specific assumptions that probably overestimate the numbers of survivors.

Source. Harwell and Hutchinson, 1986, p. 480.

G. Effects on agricultural production

156. The SCOPE-ENUWAR group concluded that it is possible that food production in the northern hemisphere, and much of the southern hemisphere, could be lost for perhaps a year after a major nuclear war. This would result from the destruction of crops, food stores, fertilizers, pesticides, fuels; the breakdown of distribution systems at the local, regional, national and international levels and the disruption of the world economic order and of trade. Reference has been made to the climatic impact on agriculture in the northern hemisphere where the most productive nations are those which would either be combatant or otherwise affected by the climatic effect of the conflict.

157. In addition to the climatic impacts, agriculture would be seriously affected by the disruption of societal infrastructure. The interruptions in technological support and energy subsidies, transportation (both for the distribution of food within countries and for import-export) and in the general order of world trade, of which agriculture forms a great part, would be considerable.

158. Modern agriculture is energy intensive. The use of fossil fuels, both as direct energy subsidies (e.g. fuel for running machinery, irrigation plant, transport) and indirect subsidies (fertilizer and pesticide production) has increased agricultural production by a factor of between 3 and 4 in developed countries during the past 45 years. Agricultural production in developing countries has only doubled in the same period.

159. Clearly, the damage to oil fields, refineries, petrochemical industries and port facilities would affect energy production, with consequences on transport, irrigation, fertilizer and pesticide manufacturing and refrigeration. Energy intensive agriculture would be most vulnerable to a disruption of energy supplies. Agriculture not dependent on large energy subsidies would be maintained, presumably at a depressed level of productivity.

160. One third of the global fertilizer production is used by developing countries and imported from the developed world. In many instances, yield is linearly related to fertilizer inputs and would decline accordingly if these were lost. For example, agriculture in China and India is fertilizer intensive, even if not unduly reliant on direct fossil fuels, and more than half of the energy subsidy to Central American agriculture is represented by fertilizers.

161. The SCOPE-ENUWAR group emphasized that their analysis is in many ways optimistic. The group concluded that malnutrition and starvation on a global scale could result from a major nuclear war that induced a change in climate. Further, that even in the absence of a climatic impact, the import-dependent nations would suffer severe shortages because the developed nations of the northern hemisphere are also the prime exporters of food, fertilizer, pesticides and agricultural technology to the developing nations.

162. Most of the countries in Africa, South America and Asia would not be targeted but would be vulnerable to an agricultural collapse. Indeed, the populations of these nations would be almost as vulnerable as those of combatant nations. In

addition to those killed directly during the conflict of the war, between 1 billion and 4 billion (1,000-4,000 million) persons could die from starvation in the chronic post war period.

IV. HEALTH AND SOCIO-ECONOMIC EFFECTS

A. Introduction

163. The direct effects of a nuclear attack as observed at Hiroshima and Nagasaki occurred on a scale incomparably smaller than anything likely to happen in a modern nuclear exchange. In the latter case, they would result from the blast and thermal waves, the initial radiation (i.e. ionizing radiation emitted during the minute following the explosion), as well from the longer-term fall-out. They have been reviewed and recently summarized in reports by WHO and the United States Institute of Medicine (WHO, 1984, 1987; IOM, 1986), to which the reader is referred for further details.

164. In addition to the immediate death, injury and damage in the targeted areas, a nuclear war may also lead to a global climatic anomaly with serious consequences to natural ecosystems and agriculture. This would have far-reaching implications for the human food supply. The ensuing malnutrition and starvation would be exacerbated by the disruption of communications, transport, financial systems and trade.

B. Blast

165. A significant amount of the total energy released from a nuclear explosion is manifested in the generation of a blast wave. This is caused by the build-up of pressure in the vaporized material of the bomb, which gives rise to a shock front that travels through the air at supersonic speed. As the wave spreads, its intensity diminishes until it is dissipated, at distances that may be tens of kilometres or more for megaton yields.

166. Blast causes direct injuries through the sudden increase in air pressure, the ballistic projection of bodies, lacerations of the respiratory system and rupture of eardrums. Injuries are also sustained from collapsing buildings and structures and from projectiles.

C. Heat

167. The thermal wave starts at the moment of the explosion, before the pressure front is yet in motion, and lasts a few seconds, vaporizing, charring and melting objects over a distance that depends on the yield and altitude at which the device was detonated. It ignites fires that may coalesce into gigantic fire storms, especially if the environment contains large quantities of easily combustible material, such as petroleum refineries, paper mills or chemical plants, within the range of the thermal pulse.

168. The hot gases rising from the fire would bring an influx of air from the periphery, creating high winds that might fan the flames into a fierce conflagration. People would die from the heat, lack of oxygen or inhalation of carbon monoxide and other toxic substances.

169. For a 1 megaton bomb exploded at an altitude of 1.5 kilometres within an area of about 350 square kilometres, almost no one would survive exposure to the thermal wave. Outside, many would suffer burns of varying severity and extent. The nature of their injuries would depend on the victims' location relative to the explosion and also the shielding offered by structures and the terrain. The number of burn victims would be three to four times greater than those caused by blast. Additional casualties from burns, blast, the inhalation of toxic materials and asphyxiation would result from secondary fires ignited by the thermal wave.

D. Radiation

1. Initial radiation

170. A nuclear explosion is accompanied by a sudden burst of radiation with major effects on the people exposed. The nature and severity of the damage would depend on the magnitude of the radiation dose (the amount of energy lost by radiation in traversing human tissue) and dose rate (dose per unit time). For example, five types of effects can be identified for radiation delivered over a short period of time:

(a) A prodromal phase with onset within minutes of the exposure involves gastro-intestinal and neuro-muscular symptoms. The former consists of nausea, vomiting, severe diarrhoea and dehydration; the latter of fatigue, apathy, listlessness, fever, headache and hypotension followed by hypotensive shock. The response reaches a maximum within 30 minutes and then subsides until the onset of the neurological or gastro-intestinal syndrome, depending on dose;

(b) The neurological syndrome becomes apparent after doses in the order of 100 grays. The symptoms are similar to those of the prodromal phase, which is followed by transient periods of depressed or enhanced motor activity leading to incapacitation and death within two days;

(c) The gastro-intestinal syndrome occurs at doses of 10-50 grays and is caused by the loss of cells lining the intestinal wall and of the resulting loss of body fluids. Death follows after six to nine days;

(d) At doses of a few grays, destruction of bone marrow cells is the dominant effect and is accompanied by drops in the lymphocyte, granulocyte and thrombocyte counts, which reach minima after 7 to 20 days depending on dose. The white blood cell depression leads to a lowering of the immune defences, allowing infections to develop and a reduction in clotting ability that may give rise to internal bleeding. Death is not inevitable and the chances of recovery are best if intensive therapy is promptly initiated - an unlikely event in the aftermath of a major nuclear exchange;

(e) In addition to these general syndromes, serious effects can also be observed on the eye, skin, oral mucosa, lungs and gonads under partial or whole-body irradiation.

171. An index of human sensitivity to ionizing radiation is given by the dose that results in an average mortality of 50 per cent during the first 60 days following the exposure. This is called the lethal dose 50 per cent (LD_{50}). Values are difficult to obtain for humans because data from a group of irradiated people, such as the victims of Hiroshima and Nagasaki, must be combined with estimates of the doses to which the victims were subjected, and the latter are still very uncertain. Such estimates as are available (22 sets are being considered by the United Nations Scientific Committee on the Effects of Atomic Radiation, including victims of bombings and of accidents and subjects exposed for therapeutical reasons) cluster around an LD_{50} of 3 grays, whole body dose. Among these a most recent estimate from the atom bomb survivors suggests that the median lethal dose at 60 days may be significantly lower. The WHO report (1987) places the estimate at 1.5 grays, and the most recent SCOPE-ENUWAR review (Moscow, March 1988) at 2.4 grays. If the human susceptibility to ionizing radiation is greater than previously thought, it follows that casualties must be higher than suggested in earlier analyses. New estimates are expected to be provided later in 1988 by the United Nations Scientific Committee on the Effects of Atomic Radiation.

2. Local fall-out

172. If the fireball contacts the Earth's surface, the material blown into the air will mix with the radioactive products released by the nuclear reactions and rapidly fall out in the vicinity of the explosion. The short-lived radio-nuclides deposited will, in their rapid decay, not only contribute to the exposure of people through penetrating radiation at high dose rates, but also through radiation that, though stopped by the integrity of the skin, may give rise to severe and extensive radiation skin burns.

173. It must be stressed that, as with other consequences of nuclear war, realistic quantitative estimates of acute effects are difficult to determine, for they are highly sensitive to assumptions on the nature of the exchange (number, yield, fission/fusion ratio of the explosions, altitude of detonation; nature of the targets and their location relative to populated - particularly industrial - centres, meteorological conditions, effectiveness of civil defence measures, etc.).

3. Intermediate and global fall-out

174. Outside the immediate area of devastation, people would be exposed to radiation from the intermediate and global fall-out caused by the injection of nuclear debris into the atmosphere. This exposure causes low doses over a long period of time. Material injected into the troposphere would be deposited in a matter of weeks largely within the latitudes where the attack takes place. The body receives a dose from gamma ray sources on the ground and in the air, as well as an internal radiation dose from radio-nuclides, such as iodine-131 and

caesium-137, which accumulate rapidly through the food chain and are ingested in contaminated food. An external dose may also be received from fall-out particles deposited on exposed skin. This may lead to serious burns caused by beta radiation.

175. Much of the debris would be injected into the stratosphere, where it would fall out over a period of years. This would contribute to human exposure, at very low rates, through the decay of long-lived fission products. These include caesium-137 (half-life 30 years), whose decay products give rise to whole-body external and internal irradiation, and strontium-90 (half-life 29 years), which, after absorption through cereals and dairy products, would deposit in bone where it would irradiate bone and blood forming cells. Carbon-14 formed in nuclear explosions would also contribute significant doses to people outside the range of destruction, but at a still lower rate and over far longer periods because of its half-life of 5,730 years.

176. If nuclear power plants, reprocessing facilities and waste storage sites were targeted, there would be releases of other, mostly long-lived, radioactive material, increasing significantly the exposure of people for a long time and at great distances. However, the spread of such material is impossible to predict, as the Chernobyl accident has shown. Locally, large "hotspots" would be created, with increased levels of radiation, which would be uninhabitable for many years.

E. Overall direct effects

177. The WHO (1987) report has reviewed a number of nuclear war scenarios. One scenario suggested that an attack on the outskirts of London using between 1 and 10 megatons would kill between 11 and 90 per cent of the inhabitants. Another envisaged a nuclear exchange between the Soviet Union and the United States involving about 1,000 megatons on each side. Deaths would amount to between 10 and 30 million in the United States and between 20 and 30 million in the Soviet Union. A third scenario envisaged a limited nuclear war in densely populated Europe involving the explosion of over 600 bombs with a total yield of some 100 megatons. Up to 90 million people might be killed. In each case, the number of serious casualties among the survivors would be of the same order as the number of deaths.

178. The doses from intermediate and global fall-out cannot be estimated accurately because, much as with estimates of initial radiation doses, they too are sensitive to many assumptions about the conduct of the war and the environmental conditions that follow. In the northern hemisphere average cumulative doses would be likely to be less than 0.5 gray delivered over a period of years (thousands of years in the case of the major eventual contributor, carbon-14) and much less in the southern hemisphere. The effects of long-term radiation would be manifested as a function of the total dose and the period over which it would be received. These would include an increased risk of cancer above the normal, expected values. At present there is little evidence for the perpetration of genetic abnormalities in succeeding generations, although this conclusion might change as clinical and statistical diagnostic methods are refined.

179. As the average doses and resulting mortality are expected to be low, it is clear that concern about the effect of long-term radiation would be overshadowed by the importance of the number of casualties arising directly from the nuclear attack and indirectly as a consequence of the disruption of the food supply and health service systems.

F. Health care of the survivors

180. Rescue, relief and care of survivors would be of immediate concern. The experience of warfare and other disasters has established a number of basic principles for health care: triage, evacuation and appropriate emergency treatment.

181. Under triage, people are placed in three groups: those who have a poor, or no, chance of survival; those who have a reasonable chance of survival if treated; and those for whom treatment can be postponed. Rapid assessment is required because delay means that more victims would be transferred from the category "survival possible" to "survival improbable or impossible".

182. In a major nuclear war, the surviving health-care professionals would be unable to provide treatment or even enough first aid to keep the injured alive. Entering the radioactive fall-out areas would present great hazards. Rescue teams would have to be monitored and, if possible, decontaminated and would have to be rotated to prevent individuals from being exposed to excessive radiation. In the prevailing chaos such measures would be very difficult and perhaps impossible.

183. Radiation victims require highly specialized facilities. For example, in France in 1978 four persons who had been accidentally exposed to very high doses of radiation were treated in sterile conditions, each receiving 50-100 transfusions of blood cells and large doses of antimycotics and antibiotics. They survived, but without such treatment they would have died. In the Chernobyl accident, intensive hospital care was given to about 200 injured and proper medical attention was given to 135,000 evacuees after mobilizing health service personnel and supplies from the whole country. Even for the limited nuclear war scenarios, involving 1 per cent of the present nuclear arsenals, there would be millions of serious casualties. Global health services could not cope with such a situation. Following a nuclear attack, triage would be at best insignificant and rescue work inadequate.

184. In the aftermath of a nuclear attack many other health problems would emerge. The lack of water would be crucial and, in most cases, it would be contaminated by radioactivity and harmful micro-organisms. Precipitation can concentrate fall-out, producing high local levels of radioactivity. Fresh water may be unsafe for drinking and food may be contaminated. Internal radiation from the inhalation and/or ingestion of radioactive isotopes would add to the radiation dose.

185. Infection is a leading cause of death in burn and radiation victims. The epidemiological pattern of disease would be altered drastically in the aftermath of a nuclear war, by impairment of the immune response, malnutrition, lack of sanitation, proliferation of insects and micro-organisms and the collapse of epidemiological surveillance and disease control.

186. The psychological state of the survivors may be gauged to a certain extent from the experiences of Hiroshima and Nagasaki. Those attacks each consisted of a single bomb; the inhabitants had no prior knowledge of nuclear weapons and help came from neighbouring untouched areas. In a major nuclear war little or no help could be expected and the widespread awareness of the effects of nuclear weapons, especially of the radiation they cause, would considerably affect the behaviour of the survivors and lead to a decrease in co-ordinated rescue and rehabilitation efforts.

187. The effects of the blast and thermal waves, radiation, poisoning from carbon monoxide and toxic chemicals released from industrial plants and burning materials (pyrotoxins), and many other factors could be expected to produce neurological and behavioural disturbances. Experience from natural disasters suggests that the majority of the survivors would suffer from an acute stress reaction, remaining in a depressed, frightened and highly vulnerable state until the cause of the disaster was seen to have passed.

G. Effects on people and socio-economic systems

188. The direct effects in targeted areas would be catastrophic, both in terms of human lives and destruction of life-supporting infrastructure. The collapse of global networks, of finance, trade and communications would exacerbate the global indirect effects on climate and its implications for food production. Both for targeted areas and non-targeted areas far from the scene of conflict the prospect would probably be one of widespread malnutrition and starvation.

189. For the purposes of the present report, socio-economic systems have two primary functions: production, which is concerned with transforming natural and other resources into the goods and services that meet the basic human needs for food, clothing, shelter, health and cultural amenities; and the consumption of these goods and services, which requires distribution and marketing. Both functions would be severely disrupted following a nuclear war.

190. The global interdependence of socio-economic systems is a key element in considering the impact of nuclear war. The world's leading economic nations, which contain most of the important economic decision-making, financial and trade centres, lie within the areas that would be directly affected in a major nuclear war. The damage to the world economy would be severe, involving the collapse of financial institutions and the existing multilateral system of payments. Financial institutions are dependent upon electronic data processing and it is possible that, in addition to the destruction of communications hardware, the loss of software and magnetically stored data would have serious effects.

191. Production is dependent upon the size of the labour force engaged in transforming resources into economic goods and services, and the productivity of their efforts. It is clear that the labour force would be greatly reduced in size by the direct effects of a nuclear war. The starvation associated with the longer-term, indirect effects would further diminish the pool of workers.

192. Production capacity would be impaired by the extensive damage to infrastructure. For example, access to natural resources would be limited because of the disruption of transport systems. Communications would be disabled by the direct effects of blast and fire and by the intense electrical overloads produced by the electromagnetic pulse generated by high altitude nuclear detonations. The shortage of equipment, machinery, spare parts and services would similarly have major industrial consequences.

193. Energy is essential for almost all aspects of the functioning of a complex economy, not simply for the maintenance of its industrial production. Power generation is geographically concentrated in oil refineries, storage tanks, thermal power generation plants and hydroelectric dams and these would therefore be vulnerable to attack and, in many cases, could be disabled or severely compromised with few nuclear warheads.

194. The energy dependence of any institution, whether a manufacturing industry or part of the service sector, is more than a simple function of its power consumption, but reflects a complex of indirect energy subsidies. For example, production of metallic copper as raw material for electrical manufacturing involves the consumption of energy during exploration, mining and transport of the ore, smelting and refining and other such processes, and distribution of the refined product.

195. Modern agriculture is also an industry, dependent upon direct and indirect energy, technology, a skilled labour force, raw materials and many other inputs. As such, it is as vulnerable to perturbations in the economy as it is to changes in climate that may follow a major nuclear conflict. The more intensive the agricultural exploitation, the more vulnerable the system.

196. The SCOPE-ENUWAR report, among others, has predicted food shortages and starvation in the aftermath of a major nuclear war, a conclusion that is supported in the present study. The destruction of transportation would make it difficult to move food supplies from sites of harvest or storage to the hungry populations. In industrialized countries, food is no longer supplied locally, but is provided by a network of enterprises that involves not only farming, animal husbandry and fishing, but also the production of farm machinery, pesticides, fertilizers, petroleum products and commercial seeds. It uses sophisticated techniques to handle the food, for example, grain elevators, slaughterhouses, cold-storage plants, flour mills, canning factories and other packaging plants. It also includes transportation, storage, marketing and distribution of foods through both wholesale and retail outlets. A breakdown in this agricultural and distributive complex would be an inevitable consequence of a major nuclear war. However, non-combatant countries are likely to suffer similar shortages because of the interruption of imports of food and because of the climatic perturbations affecting their own agricultural production. Non-combatants are therefore likely to suffer almost as severely in these respects as the countries actually targeted in a nuclear war.

197. Damage to the world economy, the disruption of communication and data processing systems, especially by the electromagnetic pulse, would severely hinder

financial institutions and the integrity of the system of international exchange and trade. This disruption of international economic relations and the global network of transportation and communications would have repercussions on distribution and consumption that reach far beyond the combatant nations involved. The absence of many manufactured products and the lack of markets for the goods and materials of developing countries would, in turn, have serious effects on the economies of those countries. As a general guide, the proportions of the imports of non-targeted countries that come from the countries likely to be targeted in a major nuclear exchange are as follows:

	Percentage
Chemicals	83.0
Food	74.2
Engineering products	72.2
Telecommunications equipment	75.0
Cars	83.0
Consumer goods, excluding textiles	88.0
Fuel	29.0

Source. GATT, 1986, and the Statistical Yearbook of the United Nations, 1985.

The impact would therefore not be limited to the physical effects of the nuclear exchange, but must include severe damage to the economic underpinnings of many nations geographically distant from the area of conflict.

H. Recovery ?

198. In the prospect of such widespread societal collapse, reliable assessments concerning the practicability and timescale of recovery cannot be made. The implications go beyond economic considerations to those of social order and the very fabric of society. It is probable that there would be a fundamental restructuring in which established prerogatives over fiscal and monetary policy, property rights, institutional integrity and other elements of social structure might be altered beyond recognition.

199. The recovery phase would depend on how fast surviving communities and national entities could re-establish such links as communications, international transportation and trade, and develop or promote alternative sources of supplies. Clearly, much of the world's surviving population would be adversely affected for many years and society would, in many instances, be reduced to conditions of self-reliance and subsistence.

200. Climatic changes and other perturbations that affect the subsistence base have occurred in the past. Some species have survived while others have not. Human societies appear to be relatively resilient and even when the worst disasters have

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eliminated functioning cultures, some survivors have often been able to migrate and establish communities elsewhere.

201. However, no natural disaster has yet occurred to human society with the synergistic and global effects that might well arise from a major nuclear war as described above. In all previous disasters, help has ultimately been received from outside the afflicted area, an option that would not be available in the context of major nuclear war. The fact remains that, as far as may be judged, long-term recovery from a major nuclear war would be uncertain.

202. Although the effects of a major nuclear war and the prospects for post-war recovery defy detailed prescription, the current scientific evidence is clear that such a conflict would produce climatic and severe long-term socio-economic consequences that are unprecedented, even when compared with the most tragic natural disasters and conflicts in history. If recovery occurred, it would be slow and difficult, and it is most unlikely that any new social order that emerges would either resemble, or be an improvement upon, that which preceded it.

203. The scientific and social studies that have led to this new appreciation of the effects of major nuclear war should continue. They should be co-ordinated on an international scale and their findings made clear to policy-makers in both the combatant and non-combatant areas - for it appears evident that none would escape the awful consequences of a major nuclear war even if the theatre of conflict was geographically restricted to a small part of the northern hemisphere.

GLOSSARY

Acclimation	The adaption of an organism to a change in environment after experiencing a gradual change in environmental variables (e.g. plants may be able to survive a fall in average temperature if acclimated but not if exposed suddenly).
Aerosol	A colloidal suspension of solids or liquid particles in a gas. The term is frequently used to cover dust, smoke and soot in air even when these are not small enough to qualify as colloid particles.
Biological clock	Mechanism underlying the periodic or rhythmic behaviour and activity shown by many plants and animals (e.g. seed germination, migration cycles).
Biomass	The weight or volume of living material in a unit area. In the current context, material of immediate biological origin (living or dead) available for combustion at the Earth's surface (this would not include fossil fuels or lumber used in construction).
Biome	Distinct, stable biogeographic communities defined by characteristic climates, geological factors, hydrological régime, etc. (e.g. deserts, rain forests, tundra, etc.).
Biosphere	The region of the planet, encompassing part of the geosphere, atmosphere and hydrosphere, in which living organisms exist.
Black rain	Rain contaminated by smoke and particulates observed at Hiroshima and Nagasaki and evidence for the early scavenging of particulates produced by nuclear fires.
Blast wave	Moving front of high-pressure air generated by the rapid expansion of gases in an explosion and which compresses the surrounding air.
Boreal forest	Northern forests, primarily coniferous but with some hardwood, south of the taiga and to the north of the mixed forest parkland, prairie or steppe.
C	Degree Celsius.
Carbon monoxide	A combustion product of carbonaceous materials, consisting of one carbon atom and one oxygen atom. Extremely toxic, its inhalation was a common cause of death in victims of the firestorms that followed bombings of the Second World War.

Cellulose	The principal constituent of plant cell walls accounting for about 30 per cent of vegetable matter.
Celsius (degrees)	Units of temperature (abbreviation C).
Combustion	The rapid chemical reaction between a fuel and oxygen (oxidation) with the evolution of heat.
Convection	Motions within a fluid or gas leading to its transport and mixing. Convection in the atmosphere usually leads to vertical movements caused by density differences resulting from changes in temperature.
Counterforce strike	Attack made against military targets, as opposed to a countervalue strike, which is an attack on non-military targets (e.g. economic or industrially important centres).
Dose (radiation)	Quantity of ionizing radiation absorbed by living tissue (see under gray).
Dust	Mineral particles, differentiated from smoke and soot, which contain carbon and which have different optical properties.
Electromagnetic pulse	High energy electromagnetic pulse of long wavelength radio frequency waves. The intense fields generated, particularly by a high-altitude nuclear detonation, can disable electrical and electronic equipment over a wide area.
El Niño	A warm southerly current off the coast of Ecuador and Peru that may exceptionally cause a temporary shift in the tropical rain belt and changing the upwelling in the ocean sufficiently to devastate marine food chains and fisheries.
ENUWAR	SCOPE study on the environmental effects of nuclear war.
Fireball	Incandescent sphere of hot gases and their associated shock front formed by the intense heat generated by thermal x-rays in the first few milliseconds following a nuclear detonation.
Fuel	In this context, any combustible material ignited directly or indirectly by nuclear weapons.
Fuel loading	The density of fuel in the target area, usually measured in units of kg km^{-2}.

General circulation model	A numerical simulation, or model, usually undertaken on powerful computers, that attempts a comprehensive description of the general (planetary) circulation, that is, the atmospheric motions over the Earth.
Genetic effect	A change (usually deleterious) in the genetic material that is transmitted to the genetic material of the offspring.
Gray	International System (SI) unit of radiation dose, 1 gray = 100 rad.
Half-life	The period, characteristic for each radioactive species, during which its activity decreases to half of its initial level.
Hardening (botanical)	Physiological process by which some plants develop seasonal resistance to low temperature and illumination.
Heat capacity (ocean)	The ratio of the amount of heat absorbed or released from a system for a given change in temperature. The large specific heat of water and the volume of the oceans means that ocean temperature will change only slowly in response to even drastic short-term changes in sunlight reaching the planet's surface.
Hydrocarbon	Literally organic compounds containing hydrogen but often used in the current context as a synonym for petrochemical fuels.
Hydrophobic	Adjective used to describe substances that have a low affinity for water (water repellent), for example, pure carbon smoke particles.
Initial radiation	Neutrons and gamma rays emitted during a conventionally defined period of one minute following the detonation of a nuclear explosion.
Insolation	Solar radiation incident at the Earth's surface (contraction, incoming solar radiation).
Ionizing radiation	Electromagnetic (gamma, x-rays) or particulate (alpha, beta, neutron) radiation that separate neutral atoms into ion pairs during their passage through materials.
Kiloton	A measurement of explosive yield approximately equivalent to that of one thousand (10^3) tons of TNT.

Latent heat	The heat energy released or absorbed by a unit mass during a change of phase, for example, the heat required to change water from a fluid to a gas.
Lethal dose	The dose of a toxic substance or radiation required to kill the exposed organism, often quantified by an LD_{50}.
LD_{50}	Dose required to kill 50 per cent of the exposed population.
Little Ice Age	Period beginning around the turn of the sixteenth century lasting into the nineteenth century during which there was an expansion of the glaciers of the northern hemisphere (sometimes regarded as several distinct episodes, or Little Ice Ages).
Lofting	The upward movement of black, carbonaceous particles (soot and smoke), and the air mass in which they are contained, when heated by solar radiation. Lofting may cause particulates to reach altitudes much greater than that to which they were initially injected by nuclear detonations and the resulting fires.
Maturation (plant)	The achievement of reproductive maturity and consequent setting of seeds, fruits, etc.
Megaton	A measurement of explosive yield approximately equivalent to that of one million (10^6) tons of TNT.
Metabolism	The totality of biochemical and physiological processes concerned with the synthesis and breakdown of living tissue and its products.
Model (simulation)	Numerical representation of a complex system, (e.g. a computer solution of a series of algorithms describing more or less completely the components of climate).
Nitrogen oxides	Compounds (normally gaseous) composed of nitrogen and oxygen some of which may be created in large quantities in the nuclear fireball and which may adversely affect the ozone layer.
Numerical simulation	The simulation of a process through approximation using numerical methods.
Optical depth	A measure of the opacity of the atmosphere.
Oxidation	In this context, the reaction of any substance to form a compound with oxygen.

Ozone	Molecule comprising three atoms of oxygen formed in the stratosphere under the action of solar radiation. It is important in maintaining the structure and movement of the atmosphere and in shielding the surface from harmful ultraviolet radiation. The stratospheric ozone layer may be damaged by emissions from nuclear fires, especially nitrogen oxides.
Photosynthesis	The photochemical synthesis of sugars from carbon dioxide and water by (normally green) autotrophic plants. With only a few exceptions this process lies at the root of all food chains and all life is dependent upon it.
Photosynthetically active radiation	The orange-red-blue part of the visible electromagnetic spectrum most efficient at stimulating photosynthesis.
Primary production	Biological production by photosynthesizing plants, the basis of all but a few food chains.
Pyrolysis	The dissociation of a chemical compound into its constituents under the action of heat (without oxidation).
Pyrotoxins	Toxic substances released from, or created in, fires.
Radio-nuclide	Radioactive nuclide or atomic species.
Reflectance (optical)	The ability of a surface of one medium to turn back incident radiation into the medium from which the radiation originated.
Residual radiation	Radiation (primarily gamma rays and beta particles) persisting long after a nuclear detonation and originating in fission products and debris made radioactive by neutron activation.
Scattering (optical)	The ability of particles, suspended in a medium of different refractive index, to diffuse some or all of the incident radiation in all directions without transforming the energy. Scattering, together with absorption, contributes to the attenuation of radiation by particles in the atmosphere.
Sensible heat	Synonym for enthalpy, a thermodynamic function of the state of a system defined in terms of its internal energy, pressure and volume. The transport of sensible heat is an important atmospheric phenomenon.

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Shock front	Pressure wave propagating outward from an explosion, caused by the compression induced in the medium (e.g. air or water) by the rapid expansion of the explosion.
Shortwave radiation	Meteorological term for solar electromagnetic radiation in the visible and near visible part of the spectrum. This is an approximate term and the spectrum is variously defined as 0.4-1.0 micrometres or 0.29-4.0 (peak 5.0) micrometres by different authorities.
Smoke emission factor	The fraction of a fuel by weight that is converted into soot or smoke during combustion. A value of 5 per cent is a representative, weighted average.
Smoke injection	The introduction of smoke (or dust and soot) into the atmosphere, either under real conditions following an explosion or as a specified condition of a computer simulation model.
Smoke loading	The amount of atmospheric smoke per unit area, usually measured in units $g\ m^{-2}$.
Solar radiation	The complete electromagnetic spectrum emitted by the sun.
Stratosphere	The atmospheric layer above the lower atmosphere (troposphere) and below the mesosphere, that is from 10-20 kilometres (depending upon latitude) at the lowest up to 20-25 kilometres. It is characterized by a persistent circulation and the presence of the ozone layer.
Synergism	The interaction of two phenomena in a manner such that their combined effect is quantitatively greater than the sum of the two taken separately.
Taiga	Swampy open woodland with abundant lichen transitional between the boreal forest and tundra.
Thermal inertia (ocean)	The delayed response of the oceans to changes in temperature in the atmosphere and Earth's surface resulting from their large volume and the high heat capacity of water.
Thermal radiation	Ultraviolet, visible and infra-red radiation emitted from a nuclear fireball. For low-altitude air bursts there is an initial pulse of UV followed by the lower energy pulse of visible and infra-red radiation.
Ton	Usually the short ton, 2,000 pounds.
Tonne	Metric tonne, 1,000 kilogrammes.

Triage	The assignment of priority in treatment of the sick when resources are inadequate for the optimal treatment of all.
Trinitrotoluene	A conventional explosive (abbreviation TNT).
Tropopause	The discontinuity between the unstable lower troposphere and the relatively stable stratosphere.
Troposphere	The lower atmosphere from the surface to an altitude of 10-20 kilometres (depending upon latitude). It is characterized by decreasing temperature with altitude, vertical wind motions and large quantities of water vapour, and is the region in which weather systems operate.
TTAPS	An acronym, based on the authors' names, for an important publication on the climatic impacts of nuclear explosions (see Turco et al., 1983, in bibliography).
Turbidity (meteorology)	The presence of smoke, dust and haze in the cloud-free atmosphere that reduces visibility.
Ultraviolet radiation	Electromagnetic radiation having shorter wavelength than the visible spectrum and longer wavelength than x-rays (400-10 nm). It is responsible for many important photochemical reactions in the atmosphere, notably the formation of stratospheric ozone. The UV range is subdivided, the UV-B (315-280 nm) spectrum being the most important biologically.
UV, UV-B	See ultraviolet radiation.
Winter wheat	A major North American and Asian crop that is sown in the autumn to germinate the following spring.
Yield (of nuclear weapon)	Explosive energy, usually expressed in units approximately equivalent to that released by a given quantity (kiloton, megaton) of conventional explosive TNT.

BIBLIOGRAPHY

Abakoumova, G. M. et al. 1986. Influence of smoke haze on the transmittance of the solar radiation and natural illumination. Meteorologia i Hydrologia, No. 11, pp. 24-30. (In Russian.)

Aleksandrov, V. V. and G. M. Stenchikov. 1983. On the modelling of the climatic consequences of the nuclear war. Proceedings of Applied Mathematics, Moscow: Computing Centre of the USSR Academy of Sciences, 1983.

Aleksandrov, V. V. and G. M. Stenchikov. 1984. Concerning a computational experiment: modelling the climatic consequences of nuclear war. Zhurnal Vycheslitel'noy Matematiki i Matematicheskoy Fiziki (Journal of Computational Mathematics and Mathematical Physics), vol. 24, No. 1, pp. 140-144. (In Russian, English translation pp. 87-90.)

Andronova, A. V. and P. P. Anikin. 1986. Investigation of aerosol formation upon combustion of various materials and their optical properties. In Combustion of Heterogeneous and Gaseous Systems, pp. 124-127. Materials of the Eighth All-Union Symposium on Combustion and Explosion. Chemical Physics Institute of the USSR Academy of Sciences.

Birks, J. W. and S. L. Stephens. 1986. Possible toxic environments following a nuclear war. In The Medical Implications of Nuclear War, eds. Solomon, F. and R. Q. Marston, pp. 155-166, National Academy Press, Washington, D.C.: Institute of Medicine. 619 p.

Brinkman, A. W. and J. McGregor. 1983. Solar radiation in dense Saharan aerosol in Northern Nigeria. Quarterly Journal Royal Meteorological Society, vol. 109, pp. 831-897.

Budyko, M. I., G. S. Golitsyn and Yu. A. Izrael. 1986. Global Climatic Catastrophes, Leningrad: Hydromet, Publishing House. 160 p.

Bush, B. H. and R. D. Small. 1987. A note on the ignition of vegetation by nuclear weapons. Combustion Science and Technology, vol. 52, pp. 25-38.

Cotton, W. R. 1985. Atmospheric convection and nuclear winter. American Scientist, vol. 73, pp. 275-280.

Covey, C. 1987. Protracted climatic effects of massive smoke injection into the atmosphere. Nature, vol. 325, pp. 701-703.

Covey, C., S. H. Schneider and S. L. Thompson. 1984. Global atmospheric effects of massive smoke injections from a nuclear war: results from general circulation model simulations. Nature, vol. 308, pp. 21-25.

Crutzen, P. J. and J. W. Birks. 1982. The atmosphere after nuclear war: twilight at noon. Ambio, vol. 11, pp. 115-125. (Reprinted in The Aftermath: The Human and Ecological Consequences of Nuclear War, ed. Peterson, J., New York: Pantheon Books, 1983. 196 p.)

Crutzen, P., I. E. Galbally, and C. Brühl. 1984. Atmospheric effects from post-nuclear fires. Climatic Change, vol. 6, pp. 323-364.

Demchenko, C. F. and A. S. Ginsburg. 1986. Influence of radiation on the vertical development of a turbid atmospheric layer. Meteorology and Hydrology, No. 6, pp. 51-57.

Dotto, L. 1986. Planet Earth in Jeopardy. Chichester, New York, Brisbane, Toronto, Singapore: John Wiley & Sons. 134 p.

Ehrlich, P. R., J. Harte, M. A. Harwell, P. H. Raven, C. Sagan, G. M. Woodwell, J. Berry, E. S. Ayensu, A. H. Ehrlich, T. Eisner, S. J. Gould, H. D. Grover, R. Herrera, H. A. Mooney, N. Myers, D. Pimentel and J. M. Teal. 1983. Long-term biological consequences of nuclear war. Science, vol. 222, pp. 1293-1300.

Ehrlich, P. R., C. Sagan, D. Kennedy and W. O. Roberts. 1984. The Cold and the Dark: The World After Nuclear War. New York: W. W. Norton & Company Inc. 229 p. (Also published in some countries as The Nuclear Winter: The World After Nuclear War, London: Sigwick and Jackson Limited, London. 227 p.)

Ganopolsky, A. N. and G. L. Stenchikov. 1987. Numerical modelling of a nuclear winter: cooling of ocean upper mixed layer and relaxation of climate. (Presented at the SCOPE-ENUWAR Workshop, Bangkok, February 1987.)

Ghan, S. J., M. C. MacCracken and J. J. Walton. 1987 a. The climatic response to large atmospheric smoke injections: sensitivity studies with a tropospheric general circulation model. Journal of Geophysical Research. (Submitted.)

Ghan, S. J., M. C. MacCracken and J. J. Walton. 1987 b. Chronic effects of large atmospheric smoke injections: interactions with the ocean mixed layer, sea ice, and ground hydrology. Paper presented at the Defense Nuclear Agency, Global Effects Program Technical Meeting, Santa Barbara, California, 7-9 April 1987.

Golitsyn, G. S. 1986 a. Climatic consequences of nuclear war. Paper presented at the ICSU Symposium on the Consequences of Nuclear War, Berne, 16 September 1986. Paris: ICSU Press.

Golitsyn, G. S. 1986 b. Nuclear winter: new developments from the USSR. Environment, vol. 28, pp. 5-44.

Golitsyn, G. S. and M. C. MacCracken. 1987. Atmospheric and climatic consequences of a major nuclear war: results of recent research. Geneva: World Meteorological Organization, WCP-142.

Golitsyn, G. S. and N. A. Phillips. 1986. Possible climatic consequences of a major nuclear war. Geneva: World Meteorological Organization, WCP-113.

Golitsyn, G. S. and A. Kh. Shukurov. 1987. Temperature effects of dust aerosols on the example of dust storms in Tadjikistan. Proceedings of the USSR Academy of Science, 1987.

Gostintsev, Yu. A. 1986. Generation, vertical distribution and climatic effects of soot from nuclear blasts. Paper presented at the Second All-Union Conference of Scientists for Peace and Nuclear War Prevention, Moscow, 27-29 May 1986.

Green, W., T. Cairns and J. Wright. 1987. New Zealand After Nuclear War. New Zealand Planning Council, Wellington, New Zealand. 166 p.

Harwell, M. A. 1984. Nuclear Winter: The Human and Environmental Consequences of Nuclear War. New York, Berlin, Heidelberg, Tokyo: Springer Verlag. 179 p.

Harwell, M. A. and T. C. Hutchinson. 1986. Environmental Consequences of Nuclear War. Volume II. Ecological and Agricultural Effects, SCOPE 28, Chichester, New York, Brisbane, Toronto, Singapore: John Wiley & Sons. 517 p.

Institute of Medicine. 1986. The Medical Implications of Nuclear War. Eds. Solomon, F. and R. Q. Marston, National Academy Press, Washington, D.C.: IOM. 619 p.

Izrael, Yu. A. 1984. Ecology and Control of the State of Environment. Leningrad: Hydromet, Publishing House. 560 p.

Kondratyev, K. Ya. and G. A. Nikolsky. 1986. Possible ecological consequences of nuclear war for atmosphere and climate. Review preprint, Moscow: Centre for International Projects. 48 p.

Kondratyev, K. Ya., O. B. Vasilyev, V. S. Grishechkin. 1971. Concerning the spectral distribution of the radiative flux of heat into the atmosphere. Doklady Acadi. Sci. USSR, vol. 198, pp. 322-327.

Malone, R. C., L. H. Auer, G. A. Glatzmaier, M. C. Wood. and O. B. Toon. 1986. Nuclear winter: three-dimensional simulations including interactive transport, scavenging and solar heating of smoke. Journal of Geophysical Research, vol. 91, pp. 1039-1053.

Malone, R. C. 1987. A comparison of Eulerian and Lagrangian methods for tracer transport in a GCM. Paper presented at the Defense Nuclear Agency Global Effects Technical Meeting, 7-9 April 1987, Santa Barbara, California.

Mulholland, G. 1986. Smoke emission. Paper presented at the Defense Nuclear Agency/National Bureau of Standards Workshop on Smoke Emission and Properties, 13-14 November 1986, Gaithersburg, Maryland.

National Research Council. 1975. Long-term Worldwide Effects of Multiple Nuclear Weapons Detonations. Washington, D.C.: National Academy Press. 213 p.

National Research Council. 1985. The Effects on the Atmosphere of a Major Nuclear Exchange. Washington, D.C.: National Academy Press. 193 p.

Patterson, E. M., C. K. McMahon and D. E. Ward. 1986. Absorption properties and graphitic carbon emission factors of forest fire. Geophysics Research Letters, vol. 13, pp. 129-132.

Penner, J. 1986. Uncertainties in the smoke source term for nuclear winter studies. Nature, vol. 324, pp. 222-226.

Peterson, J. Ed. 1983. The Aftermath: The Human and Ecological Consequences of Nuclear War. New York: Pantheon Books. 96 p.

Pittock, A. B. 1987. Nuclear Winter in Australia and New Zealand: Beyond Darkness. South Melbourne: The Macmillan Company of Australia Pty. Ltd. 264 p.

Pittock, A. B., T. P. Ackerman, P. J. Crutzen, M. C. MacCracken, C. S. Shapiro and R. P. Turco. 1986. Environmental Consequences of Nuclear War. Volume I. Physical and Atmospheric Effects, SCOPE 28, Chichester, New York, Brisbane, Toronto, Singapore: John Wiley & Sons. 360 p.

Robock, A. 1984. Snow and ice feedbacks for prolonged effects of nuclear winter. Nature, vol. 310, pp. 667-670.

Robock, A. 1988. Cooling from 1987 forest fires. Paper presented at the DNA Global Effects Program Technical Meeting, 19-21 April 1988, Santa Barbara, California.

Royal Society of Canada. 1985. Nuclear Winter and Associated Effects: A Canadian Appraisal of the Environmental Impact of Nuclear War. Ottawa: Royal Society of Canada. 382 p.

Schneider, S. H. 1987. Climate modelling. Scientific American, May 1987, pp. 72-80.

Schneider, S. H. and R. Londer. 1984. The Co-evolution of Climate and Life, San Francisco: Sierra Club Books. 563 p.

Seshu, D. V., T. Woodhead, D. P. Garrity and L. R. Oldeman. 1987. Production and vulnerability of rice as affected by weather and climate. Paper distributed at the SCOPE-ENUWAR workshop, Geneva, 16-20 November 1987.

Small, R. D. and B. H. Bush. 1985. Smoke production from nuclear explosions in non-urban areas. Science, vol. 229, pp. 46-469.

Small, R. D., B. H. Bush and M. A. Dore. 1987. SCOPE Conference paper GE.02.87, Geneva, 1987.

Small, R. D., B. H. Bush and M. A. Dore. 1988. Initial smoke distribution for nuclear winter calculations. Aerosol Science and Technology (in press).

Small, R. D. and K. E. Heikes. 1988. Early cloud formation by large area fires. Journal of Applied Meteorology (in press).

Sokolik, I. N., T. A. Tarasova and E. M. Feigelson. 1986. Optical characteristics of the smoky atmosphere and radiative heating. Meteorologia i Hydrologia, No. 11, pp. 31-36. (In Russian.)

Stenchikov, G. L. and P. Carl. 1985. Climate consequences of nuclear war: sensitivity to large-scale inhomogeneities in the initial atmospheric pollution. Preprint, GDR Academy of Sciences. 90 p.

Stenchikov, G. L. 1986. Climatic consequences of nuclear war: numerical experiments with a hydrodynamical climate model. In Climatic and Biological Consequences of Nuclear War, Moscow: Nauka, pp. 66-99.

Stephens, S. L., J. G. Calvert and J. W. Birks. 1988. Ozone as a sink for atmospheric carbon aerosols: today and following nuclear war. Paper presented at the SCOPE-ENUWAR workshop in Moscow, 21-25 March 1988.

Svirezhev, Yu. M., G. A. Alexandrov, P. L. Arkhipov, A. D. Armand, N. V. Belotelov, E. A. Denisenko, S. V. Fesenko, V. F. Krapivin, D. O. Logofet, L. L. Ovsyannikov, S. B. Pak, V. P. Pasekov, N. F. Pisarenko, V. N. Razzevaikin, D. A. Sarancha, M. A. Semenov, D. A. Smidt, G. L. Stenchikov, A. M. Tarko, M. A. Vedjushkin, L. P. Vilikova, and A. A. Voinov. 1985. Ecological and Demographic Consequences of a Nuclear War. Moscow: Computing Centre, USSR Academy of Sciences. 282 p.

Thompson, S. L., V. Ramaswamy and C. Covey. 1987. Atmospheric effects of nuclear war aerosols in General Circulation Model simulations: influence of smoke optical properties. Journal of Geophysical Research, vol. 92, No. D9, pp. 10942-10960.

Tripoli, G. J. and S. W. Kang. 1987. A numerical simulation of the smoke plume generated by a hypothetical urban fire near San Jose, California. SCOPE-ENUWAR Paper BA.01.87.

Turco, R. P., O. B. Toon, T. P. Ackerman, J. B. Pollack and C. Sagan. 1983. Nuclear winter: global consequences of multiple nuclear explosions. Science, vol. 222, pp. 1283-1292.

United Nations. 1981. Comprehensive Study on Nuclear Weapons, New York: United Nations, Sales No. E.81.I.11.

United Nations. 1985. Climatic effects of nuclear war, including nuclear winter, a compilation. General Assembly document A/40/449 and Corr.1 and 2, New York: United Nations.

Velikhov, Ye. P. 1985. (Ed.) The Night After: Climatological and Biological Consequences of Nuclear War. Moscow: Mir, 1985.

Veltishchev, N. N., A. S. Ginsburg, and G. S. Golitsyn. 1987. Comparative analysis of mass "nuclear" and natural forest fires. (Submitted Isvestia Atmos. Oceanic Physics.)

Vupputuri, R. K. R. 1986. The effect of ozone photochemistry on atmospheric and surface temperature changes due to large atmospheric injections of smoke and NO_x by a large-scale nuclear war. Atmospheric Environment, vol. 20, pp. 665-680.

World Health Organization. 1984. Effects of Nuclear War on Health and Health Services. Geneva: WHO. 176 p.

World Health Organization. 1987. Effects of Nuclear War on Health and Health Services. Second edition, Geneva: WHO. 179 p.

Woodie, W. L., D. Remetch and R. D. Small. 1984. Battlefield Fires from Tactical Nuclear Weapons. Defense Nuclear Agency, Report DNA-TR-86-235, 15 November 1984.

Xu, Guo-chang, Ghenm, Min-lian and Wu, Guo-Xiant. 1979. On an extraordinarily heavy sandstorm on April 22nd in Gansu. Acta Meteorologia Sinica, vol. 37, pp. 27-35.

Zak, B. 1987. Plume characterization studies of hydrocarbon pool fires. Paper presented at the Defense Nuclear Agency Global Effects Program Meeting, 7-9 April 1987, Santa Barbara, California.
