Executive Summary

This volume presents the results of an assessment of the climatic and atmospheric effects of a large nuclear war. The chapters in the volume follow a logical sequence of development, starting with discussions of nuclear weapons effects and possible characteristics of a nuclear war. The report continues with a treatment of the consequent fires, smoke emissions, and dust injections and their effects on the physical and chemical processes of the atmosphere. This is followed by a chapter dealing with long-term radiological doses. The concluding chapter contains recommendations for future research and study.

In assessments of this type, a variety of procedural options are available, including, for example, "worst case" analyses, risk analyses, and "most probable" analyses. All of these approaches have relevance for the subject addressed here due to the large uncertainties which surround many aspects of the problem. Some of these uncertainties are inherent in studies of nuclear war and some are simply the result of limited information about natural physical processes. In general, in making assumptions about scenarios, models, and magnitudes of injections, and in estimating their atmospheric effects, an attempt has been made to avoid "minimum" and "worst case" analyses in favor of a "middle ground" that encompasses, with reasonable probability, the atmospheric and climatic consequences of a major nuclear exchange.

The principal results of this assessment, arranged roughly in the same order as the more detailed discussions contained in the body of this volume, are summarized below. The Executive Summary of Volume II (Harwell and Hutchinson, 1985), which describes the ecological and agricultural consequences of a nuclear war, is included Appendix 1 at the end of this volume. A Glossary is included as Appendix 2 and a list of participants in the study is included as Appendix 3.

1. DIRECT EFFECTS OF NUCLEAR EXPLOSIONS

The two comparatively small detonations of nuclear weapons in Japan in 1945 and the subsequent atmospheric nuclear tests preceding the atmospheric test ban treaty of 1963 have provided some information on the direct effects of nuclear explosions. Typical modern weapons carried by today's missiles and aircraft have yields of hundreds of kilotons or more. If detonated, such explosions would have the following effects:

- In each explosion, thermal (heat) radiation and blast waves would result in death and devastation over an area of up to 500 km^2 per megaton of yield, an area typical of a major city. The extent of these direct effects depends on the yield of the explosion, height of burst, and state of the local environment. The destruction of Hiroshima and Nagasaki by atomic bombs near the end of World War II provides examples of the effects of relatively *small* nuclear explosions.
- Nuclear weapons are extremely efficient incendiary devices. The thermal radiation emitted by the nuclear fireball, in combination with the accidental ignitions caused by the blast, would ignite fires in urban/industrial areas and wildlands of a size unprecedented in history. These fires would generate massive plumes of smoke and toxic chemicals. The newly recognized atmospheric effects of the smoke from a large number of such fires are the major focus of this report.
- For nuclear explosions that contact land surfaces (surface bursts), large amounts (of the order of 100,000 tonne per megaton of yield) of dust, soil, and debris are drawn up with the fireball. The larger dust particles, carrying about half of the bomb's radioactivity, fall back to the surface mostly within the first day, thereby contaminating hundreds of square kilometers near and downwind of the explosion site. This local fallout can exceed the lethal dose level.
- All of the radioactivity from nuclear explosions well above the surface (airbursts) and about half of the radioactivity from surface bursts would be lofted on very small particles into the upper troposphere or stratosphere by the rising fireballs and contribute to longer term radioactive fallout on a global scale.
- Nuclear explosions high in the atmosphere, or in space, would generate an intense electromagnetic pulse capable of inducing strong electric currents that could damage electronic equipment and communications networks over continent-size regions.

2. STRATEGIES AND SCENARIOS FOR A NUCLEAR WAR

In the forty years since the first nuclear explosion, the five nuclear powers, but primarily the U.S. and the U.S.S.R., have accumulated very large arsenals of nuclear weapons. It is impossible to forecast in detail the evolution of potential military conflicts. Nevertheless, enough of the general principles of strategic planning have been discussed that plausible scenarios for the development and immediate consequences of a large-scale nuclear war can be derived for analysis.

- NATO and Warsaw Pact nuclear arsenals include about 24,000 strategic and theatre nuclear warheads totaling about 12,000 megatons. The arsenals now contain the equivalent explosive power of about one million "Hiroshima-size" bombs.
- A plausible scenario for a global nuclear war could involve on the order of 6000 Mt divided between more than 12,000 warheads. Because of its obvious importance, the potential environmental consequences of an exchange of roughly this size are examined. The smoke-induced atmospheric consequences discussed in this volume are, however, more dependent on the number of nuclear explosions occurring over cities and industrial centers than on any of the other assumptions of the particular exchange.
- Many targets of nuclear warheads, such as missile silos and some military bases, are isolated geographically from population centers. Nevertheless, enough important military and strategic targets are located near or within cities so that collateral damage in urban and industrial centers from a counterforce nuclear strike could be extensive. As a result, even relatively limited nuclear attacks directed at military-related targets could cause large fires and smoke production.
- Current strategic deterrence policies imply that, in an escalating nuclear conflict, many warheads might be used directly against urban and industrial centers. Such targeting would have far-reaching implications because of the potential for fires, smoke production, and climatic change.

3. THE EXTENT OF FIRES AND GENERATION OF SMOKE

During World War II, intense city fires covering areas as large as 10 to 30 square kilometers were ignited by massive incendiary bombing raids, as well as by the relatively small nuclear explosions over Hiroshima and Nagasaki. Because these fires were few in number and distributed over many months, the total atmospheric accumulation of smoke generated by these fires was small. Today, in a major nuclear conflict, thousands of very intense fires, each covering up to a few hundred square kilometers, could be ignited simultaneously in urban areas, fossil fuel processing plants and storage depots, wildlands, and other locations. Because there have never been fires as large and as intense as may be expected, no appropriate smoke emission measurements have been made. Estimates of emissions from such fires rely upon extrapolation from data on much smaller fires. This procedure may introduce considerable error in quantifying smoke emissions, especially in making estimates for intense fire situations.

- About 70% of the populations of Europe, North America and the Soviet Union live in urban and suburban areas covering a few hundred thousand square kilometers and containing more than ten thousand million tonne of combustible wood and paper. If about 25–30% of this were to be ignited, in just a few hours or days, tens of millions to more than a hundred million tonne of smoke could be generated. About a quarter to a third of the emitted smoke from the flaming combustion of this material would be amorphous elemental carbon, which is black and efficiently absorbs sunlight.

- Fossil fuels (e.g., oil, gasoline, and kerosene) and fossil fuel-derived products (including plastics, rubber, asphalt, roofing materials, and organochemicals) are heavily concentrated in cities and industrial areas; flaming combustion of a small fraction (~25–30%) of the few thousand million tonne of such materials currently available could generate 50–150 million tonne of very sooty smoke containing a large fraction (50% or greater) of amorphous elemental carbon. About 25–30% of the combustible materials of the developed world are contained in less than one hundred of the largest industrialized urban areas.
- Fires ignited in forests and other wildlands could consume tens to hundreds of thousands of square kilometers of vegetation over days to weeks, depending on the state of the vegetation, and the extent of firespread. These fires could produce tens of millions of tonne of smoke in the summer half of the year, but considerably less in the winter half of the year. Because wildland fire smoke contains only about 10% amorphous elemental carbon, it would be of secondary importance compared to the smoke created by urban and industrial fires, although its effects would not be negligible.
- The several tens of millions of tonne of sub-micron dust particles that could be lofted to stratospheric altitudes by surface bursts could reside in the atmosphere for a year or more. The potential climatic effects of the dust emissions, although substantially less than those of the smoke, also must be considered.

4. THE EVOLUTION AND RADIATIVE EFFECTS OF THE SMOKE

The sooty smoke particles rising in the hot plumes of large fires would consist of a mixture of amorphous elemental carbon, condensed hydrocarbons, debris particles, and other substances. The amount of elemental carbon in particles with effective spherical diameters on the order of 0.1 μm to perhaps 1.0 μm would be of most importance in calculating the potential effect on solar radiation. Such particles can be spread globally by the winds and remain suspended for days to months.

- Large hot fires create converging surface winds and rapidly rising fire plumes which, within minutes, can carry smoke particles, ash and other fire products, windblown debris, and water from combustion and the surrounding air to as high as 10–15 kilometers. The mass of particles deposited aloft would depend on the rate of smoke generation, the intensity of the fire, local weather conditions, and the effectiveness of scavenging processes in the convective column.

- As smoke-laden, heated air from over the fire rises, adiabatic expansion and entrainment would cause cooling and condensation of water vapor that could lead, in some cases, to the formation of a cumulonimbus cloud system. Condensation-induced latent heating of the rising air parcels would help to loft the smoke particles to higher altitudes than expected from the heat of combustion alone.
- Although much of the water vapor drawn up from the boundary layer would condense, precipitation might form for only a fraction of the fire plumes. In the rising columns of such fires, soot particles would tend to be collected inefficiently by the water in the cloud. Smoke particles however, are generally composed of a mixture of substances and might, at least partially, be incorporated in water droplets or ice particles by processes not now well understood. Smoke particles that are captured could again be released to the atmosphere as the ice or water particles evaporate in the cloud anvils or in the environment surrounding the convective clouds. Altogether, an unknown fraction of the smoke entering the cloud would be captured in droplets and promptly removed from the atmosphere by precipitation.
- Not all fires would, however, induce strong convective activity. This depends on fuel loading characteristics and meteorological conditions. It is assumed in current studies that 30–50% of the smoke injected into the atmosphere from all fires would be removed by precipitation within the first day, and not be available to affect longer-term large-scale, meteorological processes. This assumption is a major uncertainty in all current assessments. For the fire and smoke assumptions made in this study, the net input of smoke to the atmosphere after early scavenging is estimated to range from 50 to 150 million tonne, containing about 30 million tonne of amorphous elemental carbon.
- Smoke particles generated by urban and fossil fuel fires would be strong absorbers of solar radiation, but would be likely to have comparatively limited effects on terrestrial longwave radiation, except perhaps under some special circumstances. If 30 million tonne of amorphous elemental carbon were produced by urban/industrial fires and spread over Northern Hemisphere mid-latitudes, the insolation at the ground would be reduced by at least 90%. The larger quantities of smoke that are possible in a major nuclear exchange could reduce light levels under dense patches to less than 1% of normal, and, after the smoke has spread widely, to just several percent of normal on a daily average.
- Because of the large numbers of particles in the rising smoke plumes and

the very dense patches of smoke lasting several days thereafter, coagulation (adhering collisions) would lead to formation of fewer, but somewhat larger, particles. Coagulation of the particles could also occur as a result of coalescence and subsequent evaporation of rain droplets or ice particles. Because optical properties of aerosols are dependent on particle size and morphology, the aggregated aerosols may have different optical properties than the initial smoke particles, but the details, and even the sign, of such changes are poorly understood. The optical properties of fluffy soot aggregates that may be formed in dense oil plumes, however, seem to be relatively insensitive to their size. This is less the case for more consolidated particle agglomerates.

- Little consideration has yet been given to the possible role of meteorological processes on domains between fire plume and continental scales. Mesoscale and synoptic-scale motions might significantly alter, mix, or remove the smoke particles during the first several days. Studies to examine quantitatively the microphysical evolution of smoke particles during this period are needed. While changes in detailed understanding are expected, a significant fraction of the injected smoke particles is likely to remain in the atmosphere and affect the large-scale weather and climate.

5. SMOKE-INDUCED ATMOSPHERIC PERTURBATIONS

In a major nuclear war, continental scale smoke clouds could be generated within a few days over North America, Europe, and much of Asia. Careful analysis and a hierarchy of numerical models (ranging from one-dimensional global-average to three-dimensional global-scale models) have been used to estimate the transport, transformation, and removal of the smoke particles and the effects of the smoke on temperature, precipitation, winds, and other important atmospheric properties. All of the simulations indicate a strong potential for large-scale weather disruptions as a result of the smoke injected by extensive post-nuclear fires. These models, however, still have important simplifications and uncertainties that may affect the fidelity and the details of their predictions. Nonetheless, these uncertainties probably do not affect the general character of the calculated atmospheric response.

- For large smoke injections reaching altitudes of several kilometers or more and occurring from spring through early fall in the Northern Hemisphere, average land surface temperatures beneath dense smoke patches could decrease by 20–40°C below normal in continental areas within a few days, depending on the duration of the dense smoke pall and the particular meteorological state of the atmosphere. Some of these patches could be carried long distances and create episodic cooling. During this initial period of smoke dispersion, temperature anomalies could be spatially and temporally quite variable while patchy smoke clouds strongly modulate the insolation reaching the surface.

- Smoke particles would be spread throughout much of the Northern Hemisphere within a few weeks, although the smoke layer would still be far from homogeneous. For spring to early fall injections, solar heating of the particles could rapidly warm the smoke layer and lead to a net upward motion of a substantial fraction of the smoke into the upper troposphere and stratosphere. The warming of these elevated layers could stabilize the atmosphere and suppress vertical movement of the air below these layers, thereby extending the lifetime of the particles from days to perhaps several months or more.
- Average summertime land surface temperatures in the Northern Hemisphere mid-latitudes could drop to levels typical of fall or early winter for periods of weeks or more with convective precipitation being essentially eliminated, except possibly at the southern edge of the smoke pall. Cold, near-surface air layers might lead initially to fog and drizzle, especially in coastal regions, lowland areas, and river valleys. In continental interiors, periods of very cold, mid-winter-like temperatures are possible. In winter, light levels would be strongly reduced, but the initial temperature and precipitation perturbations would be much less pronounced and might be essentially indistinguishable in many areas from severe winters currently experienced from time to time. However, such conditions would occur simultaneously over a large fraction of the mid-latitude region of the Northern Hemisphere and freezing cold air outbreaks could penetrate southward into regions that rarely or never experience frost conditions.
- In Northern Hemisphere subtropical latitudes, temperatures in any season could drop well below typical cool season conditions for large smoke injections. Temperatures could be near or below freezing in regions where temperatures are not typically strongly moderated by warming influence from the oceans. The convectively driven monsoon circulation, which is of critical importance to subtropical ecosystems, agriculture, and is the main source of water in these regions, could be essentially eliminated. Smaller scale, coastal precipitation might, however, be initiated.
- Strong solar heating of smoke injected into the Northern Hemisphere between April and September would carry the smoke upwards and equatorward, strongly augmenting the normal high altitude flow to the Southern Hemisphere (where induced downward motions might tend to slightly suppress precipitation). Within one or two weeks, thin, extended smoke layers could appear in the low to mid-latitude regions of the Southern Hemisphere as a precursor to the development of a more uniform veil of smoke with a significant optical depth (although substantially smaller than in the Northern Hemisphere). The smoke could induce modest cooling of land

areas not well buffered by air masses warmed over nearby ocean areas. Since mid-latitudes in the Southern Hemisphere would already be experiencing their cool season, temperature reductions would not likely be more than several degrees. In more severe, but less probable, smoke injection scenarios, climatic effects in the Southern Hemisphere could be enhanced significantly, particularly during the following austral spring and summer.

- Much less analysis has been made of the atmospheric perturbations following the several week, acute climatic phase subsequent to a nuclear war involving large smoke injections. Significant uncertainties remain concerning processes governing the longer-term removal of smoke particles by precipitation scavenging, chemical oxidation, and other physical and chemical factors. The ultimate fate of smoke particles in the perturbed atmospheric circulation is also uncertain, both for particles in the sunlit and stabilized upper troposphere and stratosphere and in the winter polar regions, where cooling could result in subsidence that could move particles downward from the stratosphere to altitudes where they could later be scavenged by precipitation.
- Present estimates suggest that smoke lofted (either directly by fire plumes or under the influence of solar heating) to levels which are, or become, stabilized, could remain in the atmosphere for a year or more and induce long-term (months to years) global-scale cooling of several degrees, especially after the oceans have cooled significantly. For such conditions, precipitation could also be reduced significantly. Reduction of the intensity of the summer monsoon over Asia and Africa could be a particular concern. Decreased ocean temperatures, climatic feedback mechanisms (e.g., ice-albedo feedback), and concurrent ecological changes could also prolong the period of meteorological disturbances.

6. ATMOSPHERIC CHEMISTRY IN A POST-NUCLEAR-WAR ENVIRONMENT

Nuclear explosions and the resultant fires could generate large quantities of chemical compounds that might themselves be toxic. In addition, the chemicals could alter the atmospheric composition and radiative fluxes in ways that could affect human health, the biosphere, and the climate.

- Nitrogen oxides (NO_x) created in nuclear fireballs would be lofted primarily into the stratosphere for explosions of greater than several hundred kilotons. Depending on the total number of high yield weapons exploded, the NO_x would catalyze chemical reactions that, within a few months time, could reduce Northern Hemisphere stratospheric ozone concentrations by 10 to 30% in an atmosphere free of aerosols. Recovery would take several years. However, if the atmosphere were highly perturbed due to smoke heating and by injection of gaseous products from fires, the long-term ozone changes could be enhanced substantially in ways that cannot yet be predicted.

- Stratospheric ozone reductions of tens of percent could increase surface intensities of biologically-active ultraviolet (UV) radiation by percentages of up to a few times as much. The presence of smoke would initially prevent UV-radiation from reaching the surface by absorbing it. The smoke, however, might also prolong and further augment the long-term ozone reduction as a result of smoke-induced lofting of soot and reactive chemicals, consequent heating of the stratosphere, and the occurrence of additional chemical reactions.
- Large amounts of carbon monoxide, hydrocarbons, nitrogen and sulfur oxides, hydrochloric acid, pyrotoxins, heavy metals, asbestos, and other materials would be injected into the lower atmosphere near the surface by flaming and smoldering combustion of several thousand million tonne of cellulosic and fossil fuel products and wind-blown debris. Before deposition or removal, these substances, some of which are toxic, could be directly and/or indirectly harmful to many forms of life. In addition, numerous toxic chemical compounds could be released directly into the environment by blast and spillage, contaminating both soil and water. This complex and potentially very serious subject has so far received only cursory consideration.
- If the hydrocarbons and nitrogen oxides were injected into an otherwise unperturbed troposphere, they could enhance average background ozone concentrations several-fold. Such ozone increases would not significantly offset the stratospheric ozone decrease, which also would be longer lasting. It is highly questionable, however, whether such large ozone increases could indeed occur in the presence of smoke because ozone generation in the troposphere requires sunlight as well as oxides of nitrogen. It is possible that, in the smoke perturbed atmosphere, the fire-generated oxides of nitrogen could be removed before photochemical ozone production could take place.
- Precipitation scavenging of nitrogen, sulfur, and chlorine compounds dispersed by the fire plumes throughout the troposphere could increase rainfall acidity by about an order of magnitude over large regions for up to several months. This increased acidity might be neutralized to some degree by alkaline dust or other basic (as opposed to acidic) compounds.
- Rapid smoke-induced cooling of the surface under dense smoke clouds could induce the formation of shallow, stable cold layers that might trap chemical emissions from prolonged smoldering fires near the ground. In such layers, concentrations of CO, $HC\ell$, pyrotoxins, and acid fogs could reach dangerous levels. The potential for local and regional effects in areas such as populated lowland areas and river valleys merits close attention.

7. RADIOLOGICAL DOSE

Near the site of an explosion, the health effects of prompt ionizing radiation from strategic nuclear warheads would be overshadowed by the effects of the blast and thermal radiation. However, because nuclear explosions create highly radioactive fission products and the emitted neutrons may also induce radioactivity in initially inert material near the detonation, radiological doses would be delivered to survivors both just downwind (local fallout) and out to hemispheric and global scales (global fallout).

- Local fallout of relatively large radioactive particles lofted by the number of surface explosions in the scenario postulated in this study could lead to lethal external gamma-ray doses (assuming no protective action is taken) during the first few days over about 7 percent of the land areas of the NATO and Warsaw Pact countries. Areas downwind of missile silos and other hardened targets would suffer especially high exposures. Survivors outside of lethal fallout zones could still receive debilitating radiation doses (exposure at half the lethal level can induce severe radiation sickness). In combination with other injuries or stresses, such doses could increase mortality. If large populations could be mobilized to move from highly radioactive zones or take substantial protective measures, the human impact of fallout could be greatly reduced.
- The uncertainty in these calculations of local fallout is large. Doses and areas for single nuclear explosions could vary by factors of 2–4 depending on meteorological conditions and assumptions in the models. A detailed treatment of overlapping fallout plumes from multiple explosions could increase the areas considerably (by a factor of 3 in one sample case). Results are also sensitive to variations in the detonation scenario.
- Global fallout following the gradual deposition of the relatively small radioactive particles created by strategic air and surface bursts could lead to average Northern Hemisphere lifetime external gamma ray doses on the order of 10 to 20 rads. The peak values would lie in the northern mid-latitudes where the average doses for the scenarios considered would be about 20 to 60 rads. Such doses, in the absence of other stresses, would be expected to have relatively minor carcinogenic and mutagenic effects (i.e., increase incidence at most a few percent above current levels). Smoke-induced perturbations that tend to stabilize the atmosphere and slow deposition of radioactive particles might reduce these estimated average doses by perhaps 15%.
- Intermediate time scale and long term global fallout would be deposited unevenly, largely because of meteorological effects, leading to "hotspots" of several hundred thousand square kilometers in which average doses could be as high as 100 rads, and, consequently, large areas where doses would be lower than the average value.

- In the Southern Hemisphere and tropical latitudes, global fallout would produce much smaller, relatively insignificant, radiological doses about one-twentieth those in the Northern Hemisphere, even if cross-equatorial transport were accelerated by the smoke clouds. Additional local fallout would be important only within a few hundred kilometers downwind of any surface burst in the Southern Hemisphere.
- Additional considerations not factored into the above estimates are possible from several sources. Doses from ingestion or inhalation of radioactive particles could be important, especially over the longer term. Beta radiation could have a significant effect on the biota coming into contact with the local fallout. Fission fractions of smaller modern weapons could be twice the assumed value of 0.5; adding these to the scenario mix could cause a 20% increase in areas of lethal fallout. General tactical and theater nuclear weapons, ignored in these calculations, could also cause a 20% increase in lethal local fallout areas in certain geographical regions, particularly in Europe. The injection into the atmosphere of radionuclides created and stored by the civilian nuclear power industry and military reactors, a possibility considered remote by some, could increase estimates of long-term local and global radiological doses to several times those estimated for weapons alone.

8. TASKS FOR THE FUTURE

Extensive research and careful assessment over the past few years have indicated that nuclear war has the potential to modify the physical environment in ways that would dramatically impair biological processes. The perturbations could impact agriculture, the proper functioning of natural ecosystems, the purity of essential air and water resources, and other important elements of the global biosphere. Because current scientific conclusions concerning the response of the atmosphere to the effects of nuclear war include uncertainties, research can and should be undertaken to reduce those uncertainties that are accessible to investigation.

- Laboratory and field experiments are needed to improve estimates of the amount and physical characteristics of the smoke particles that would be produced by large fires, particularly by the combustion of fossil fuels and fossil fuel-derived products present in urban and industrial regions. Experimental conditions should be designed to emulate as much as possible the effects of large-scale fires.
- Laboratory, field, and theoretical studies are needed to determine the potential scavenging rates of smoke particles in the convective plumes of large fires and the scavenging processes that operate on intermediate and global scales as the particles disperse.

- Further theoretical calculations of the seasonal response of the atmosphere to smoke emissions from large fires are needed, particularly of the extent of the perturbation to be expected at early times, when the smoke is freshly injected and patchy. Simulations must be made for later times from months to a year or more, when the atmosphere has been highly perturbed and a substantial fraction of the smoke may have been lofted to high altitudes. Closer attention should be paid to the possible effects in low latitudes and in the Southern Hemisphere, where the climatic effects are likely to be much more important than the direct effects of the nuclear detonations, which are expected to be confined largely to the Northern Hemisphere.
- Laboratory and theoretical studies are needed of the potential chemical alterations of the atmosphere on global and local scales, and of the extent that smoke particles could affect and might be removed by chemical reactions high in the atmosphere.
- Radiological calculations should be undertaken using models that more realistically treat the overlap of fallout plumes, complex meteorological conditions, and that consider both external and internal doses. Patterns of land use and likely targeting strategy should be used in estimating the potential significance of various scenarios. The question of the possible release of radioactivity from nuclear fuel cycle facilities in a nuclear war should be explored more thoroughly.