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PREFACE

It was recognized in 1982 that smoke injected into the atmosphere by fires started by a major nuclear war could cause significant atmospheric perturbations. Research on that topic and, especially, the more comprehensive analyses of the potential environmental consequences carried out in the last few years, have essentially confirmed that significant atmospheric perturbations, affecting weather and climate, could be induced by such an event.

At the request of the WMO Executive Council, the Joint Scientific Committee for the World Climate Research Programme (JSC) has undertaken to review the available scientific evidence about this problem every second year. The first JSC review was prepared by G.S. Golitsyn and N.A. Phillips in 1985, and published in 1986. The present document, prepared by G.S. Golitsyn and M.C. MacCracken, was discussed by the JSC at its eighth session in Castelvecchio Pascoli, Italy, 23-27 March 1987. This document, which incorporates the remarks and points of clarification made by the JSC, constitutes an up-to-date review of the results of studies carried out by many research groups throughout the world up to the end of 1986. The current draft of this review will be made available for information to the Tenth World Meteorological Congress in May 1987 before its publication in the World Climate Progamme Reports series.

SUMMARY:

Recognition in 1982 that smoke injected into the atmosphere by fires started by a major nuclear war could induce significant perturbations in weather and climate has led, during the past few years, to more detailed and comprehensive analyses of the potential environmental consequences of such a catastrophe. Since the initial studies, which were reviewed by the Joint Scientific Committee for the World Climate Research Programme (Golitsyn and Phillips, 1986), extensive research has confirmed that considerable atmospheric perturbations would result from a major nuclear war, although important uncertainties remain.

Available scientific information indicates that a major nuclear exchange involving a significant fraction of the potentially combustible materials could ignite fires that would inject tens to hundreds of teragrams (millions of tonne) of dark smoke into the atmosphere. The optical properties of the smoke would be strongly dependent upon the amount of petroleum, artificial polymers and related products burned and the conditions under which the cellulosic materials burned. Recent laboratory and modelling results suggest that the particles emitted by the fires may be more highly absorbing of solar radiation than previously thought because of their unconsolidated character. Combining plausible, but uncertain, estimates of the factors contributing to initial smoke production suggests a range of a few tenths to a few for the initial hemispheric-average absorption optical depth of the smoke following the extreme case of a nuclear war involving urban targets and oil refineries. Because the uncertainties are large, the possibility of generating larger or smaller amounts of smoke cannot be ruled out; other less extreme exchanges, however, could involve fewer targets and therefore less smoke. The uncertainty in the amount of smoke generated is a major contributor to the range of possible climatic impacts that have been projected, such that the perturbation could be only several degrees and short-lived or a few tens of degrees for weeks followed by lesser, but much longer-lasting perturbations. Although some of the factors depend on specific assumptions about the nuclear exchange, better estimates of many of the factors can be developed by inventorying of combustible materials and by laboratory, field, and modelling studies.

From the time of their initial generation out to a first few days after injection, the smoke particles would be strongly affected by transformation and scavenging processes. Although important progress has been made in the modelling of fire plumes and the study of the microphysical properties of smoke particles, large uncertainties remain in estimating the rates of scavenging and the evolution of the optical properties of the particles. However, only limited progress has been made in estimating smoke-atmosphere interactions on mesoscale domains. In recent modelling studies, the extent of scavenging in fire plumes has been found to depend on the fraction of particles serving as condensation nuclei and the particular representation of ice processes in the models being used. Assuming mid-range smoke estimates and that about half of the smoke is removed in fire plume processes, a major nuclear war could result in a hemispheric-average absorption optical depth of the order of unity (referred to hereafter as a baseline case).

It is recognized that this amount of smoke would cause global atmospheric perturbations, particularly if the war were to occur during the spring or summer months. During the first month, the sunlight reaching the surface in northern hemisphere mid-latitudes could be reduced by 80% or more, resulting in zonal mean land temperatures up to 20°C below normal two weeks after injection of smoke during northern summer (but 15–30°C below normal in central continental areas). The studies of the climatic impact of a baseline summertime smoke injection, conducted with three-dimensional atmospheric circulation models and comprehensive representations of physical processes, indicate that mean land temperatures could drop to at or slightly above the freezing level with transient regional episodes of sub-freezing temperatures. The present model calculations do not find the "deep freezes" suggested by the early results obtained with simplified one-dimensional and three-dimensional atmospheric models. On the other hand, these recent studies emphasize the plausibility of a serious reduction of precipitation over continents and a disruption of the summer monsoon, even with only moderately obscuring smoke amounts. Finally, the expectation of upward lofting of smoke into the stratosphere and subsequent transport of a large amount of smoke into the southern hemisphere during

the first month following a warm season war have been generally confirmed, although moderation of these effects by dust injections may occur. The potential exists for perturbation of stratospheric ozone by explosion-induced nitrogen oxide injection, by the perturbed atmospheric state, and by reactions with smoke particles (which may be an important sink mechanism for the smoke particles and/or for the ozone itself); these chemistry-related issues may be important determinants of the overall climatic effects, but all are poorly understood.

As the smoke is dispersed and removed by atmospheric processes, climatic effects are expected to change. Beyond one month, the large perturbation of northern hemisphere temperatures is expected to decrease, although it is not known how rapidly. At the same time, the smoke could have spread over much of the earth, causing a reduction in sunlight of the order of 20% and depressing temperatures to several degrees below normal. There have been, so far, few model simulations extending to one year or more. Preliminary results of such simulations suggest that spring and summer climatic conditions could be significantly affected in the year following the fires, especially if smoke removal from the stratosphere is slowed. The meteorological and physical uncertainties are such that reliable quantitative conclusions regarding the effects of the injection of a specified amount of smoke in northern mid-latitudes cannot yet be reached, however, for periods beyond more than a few weeks in the northern hemisphere nor, at any time, in the tropics and the southern hemisphere.

Most studies to date have considered solely the effects of injection of carbonaceous smoke into the atmosphere. It is recognized, however, that a major nuclear exchange would cause the injection of many other radiatively or chemically active gases and particles, toxins, and other substances. For example, sub-micron diameter dust particles lofted into the stratosphere by high-yield explosions could cause effects equivalent to that of a very large volcanic eruption, i.e., a mean surface cooling of the order of 1°C or more over a year or longer. On the other hand, the injection of a large amount of dust to altitudes above the smoke could inhibit the subsequent smoke ascent into the upper troposphere and stratosphere and moderate the transport of smoke into the southern hemisphere. Further, nitrogen oxides produced at the high temperatures of the shock-waves and fireballs could deplete stratospheric ozone significantly. The coupled chemical-dynamical simulations needed to assess whether the perturbed atmospheric circulation could further reduce stratospheric ozone have not yet been performed.

During the last several years, a wide range of capabilities, including comprehensive three-dimensional atmospheric circulation models and detailed parametric formulations of a wide range of climatologically significant processes, have been applied to study the potential consequences of a major nuclear exchange and the injection of smoke that could result from the large-scale fires ignited by such an exchange. It is obvious that these studies have been made possible by the development of realistic climate models. In the face of the many remaining oversimplifications and deficiencies, the on-going WCRP activities aiming to refine the climate models will help to narrow the uncertainties while an even wider field of atmospheric physics and chemistry needs to be investigated to arrive at a more quantitative assessment of the overall environmental impacts of a major nuclear war.

1. INTRODUCTION

The suggestion made in 1982 by Crutzen and Birks, that the smoke generated by the fires resulting from a nuclear exchange could be sufficient to substantially reduce the solar radiation reaching vast areas of the earth's surface, provided the original scientific insight into this aspect of the consequences of nuclear war. Initial estimates of the climatic perturbations created by such massive smoke injections were then carried out by Turco et al. (1983). Subsequent calculations carried out in the USA and USSR confirmed the possibility that a large and rapid cooling could occur over land areas in the northern hemisphere because of the formation of a high-altitude smoke layer which would absorb solar radiation above the level where the normal atmospheric greenhouse effect is most effective. The scientific findings on the climatic impacts of nuclear war that were available by the end of 1984 were reviewed by Golitsyn and Phillips (1986) and discussed by the WMO/ICSU Joint Scientific Committee for the World Climate Research Programme (JSC-VI, 1985). More complete discussions of the scientific basis for assessing the consequences of a nuclear war on weather and climate can be found in a publication of the National Research Council of the USA (NRC, 1985), a publication by Budyko et al. (1986), and a number of additional reviews, the most detailed and authoritative of which is the two-volume work "Environmental Consequences of Nuclear War" published in early 1986 by the SCOPE-ENUWAR project. The first volume of the SCOPE-ENUWAR project (Pittock et al., 1986) reviews the potential physical and atmospheric effects of a major nuclear war and the second volume (Harwell and Hutchinson, 1986) provides an inventory of possible impacts to natural and agricultural systems and food supplies.

The last two years have seen continuing progress in understanding. A number of numerical experiments have been performed with more comprehensive, but still incomplete, general circulation models. These calculations have examined the sensitivity of the results to the amount of smoke, its distribution with height, its optical properties, the rate of scavenging, and other factors. In addition to the temperature reduction found in initial studies, these experiments have confirmed the plausibility of additional effects that had been suggested by earlier qualitative analyses, including reduction of precipitation, monsoon damping during the summer, and smoke lofting into the stratosphere. Preliminary estimates of the longer-term "chronic" effects have also recently been made by extending climate calculations over time spans of the order of a year (or more). These results suggest that the surface temperature could be reduced in the subsequent warm season by several degrees for scenarios generating substantial smoke injections, although large uncertainties remain involving, particularly, the processes controlling the rate of removal of the smoke from the atmosphere. There have also been more detailed studies, both theoretical and experimental, of the smoke yields from combustion of various materials, size distribution and coagulation of smoke particles, and changes in smoke optical and microphysical properties with time. Analyses have also been conducted of the influence of smoke on the thermal and radiative regime at the surface.

Results from studies over the past two years have reduced some of the uncertainties, clarified the nature and importance of others, and identified new problems and limitations. This report provides an overview of these new results. Our analysis finds that the main conclusion of the Golitsyn and Phillips (1986) report remains valid. Despite the remaining uncertainties, which could either moderate or amplify some of the processes in the long chain of events leading to climatic consequences, a substantial global-scale climatic perturbation would result from the injection of a large amount of smoke into the atmosphere, particularly during the warm half of the year.

2. FUEL LOADING, FIRES and SMOKE

The potential climatic effects of smoke injections depend on the amount of smoke created in the fires and its physical and optical properties. These, in turn, are dependent on the amount and type of materials that are ignited and the conditions under which the burning takes place. Not all of these factors can be determined, some being strongly dependent on the particular conditions under which the nuclear weapons are used (e.g., characteristics of targets, atmospheric visibility in target areas, etc.), but bounds can be placed on many of the factors and plausible assumptions (e.g., using climatology) can be made for others. All estimates of the smoke amount that could be released in a major nuclear war (Crutzen and Birks, 1982; Turco et al., 1983; NRC, 1985; Pittock et al., 1986; Penner, 1986a) are based on such assumptions. While generally beyond the purview of the Joint Scientific Committee, it is important to understand the status of research on this topic. This section reviews the status of research in this area.

2.1 Fuel Loading

Estimates of the amount and character of the materials that would be ignited in a nuclear war have been made using two different approaches. Turco et al. (1983) and NRC (1985) estimated the average loading of combustible material per unit area in various target areas and then multiplied by an estimate of the area that would be exposed to an ignition thermal flux from an assumed distribution of nuclear fireballs. The area that might be exposed to plausible ignition fluxes depends in part on meteorological conditions, especially atmospheric humidity, turbidity, and, in part, on the altitude and yield of the explosion. For a 1 Mt explosion, the area receiving sufficient thermal radiation to cause ignition of common materials ranges from 50 to 1000 square kilometers. Due to the likelihood of overlapping explosions, the limited sizes of urban areas, and other factors, a value of 250–500 square kilometres per megaton has generally been used, varying as the square root of the explosive yield. Because average fuel loadings were originally overestimated (Penner, 1986a) and are still poorly known and the pattern of explosions is poorly known, this method can be rather inaccurate and is no longer preferred.

Crutzen et al. (1984) and Pittock et al. (1986) took the alternative approach of developing inventories of the amount of combustible material present in potential target countries and assuming that a fraction of this would burn. [A third approach based on a very detailed analysis of a representative set of targets is now being carried out as a check on the validity of the other approaches (Small et al., 1987), although it also involves a number of approximations.] Two somewhat independent estimates of the inventory of combustible materials (Crutzen et al., 1984; Bing, 1985) suggest that 6000 to 17000 Tg of cellulosic materials and 1300 to 1500 Tg of petroleum and polymeric materials can be found in the NATO and Warsaw Pact nations. The range of estimates in the amount of cellulosic materials appears to be related either to assumptions about the amount of wood used in buildings in Europe and the Soviet Union, which should be resolvable through actual surveys of representative areas, or to inaccurate estimates of the average period of use (lifetime) of wood and wood products.

Developing detailed estimates of how much of the potentially-combustible material would burn would require detailed analyses of particular scenarios, taking into account the number and location of explosions, the overlap of multiple explosions, exposure, flammability limits, visibility, etc. Because this is not practical (or perhaps even possible), plausible estimates of the burned fraction must be used instead. For example, about two-thirds of the combustible fuel is associated with urban populations; one might assume that 75% of this fuel would be in targeted cities themselves (or sufficiently close to other targets) and that half of this material would be consumed in flaming combustion (i.e., assuming half would be buried in the rubble and be so distributed that it would burn slowly, if at all); combining these factors, 25% of the total combustible fuel load would then be burned. Estimates for the fraction burned used in various studies go up to 50%; such a value may be too high, unless spread of the fires is an important contributing factor (Tripoli and Kang, 1987; Reitter, 1986) or rubblized areas burn vigorously. On the other hand, almost all of the petroleum fuel stocked in refineries could be ignited and consumed in flaming combustion.

It is interesting that the initial concern for climatic effects of a nuclear war arose from the estimated smoke that might be generated by burning of woodlands (Crutzen and Birks, 1982). Closer examination of the potential non-urban targets has shown that most are in grassland or agricultural areas, at least in the United States, where the potential fuel load is so low that only a few teragrams of smoke would be generated (Small and Bush, 1985). Pittock et al. (1986), however, discuss several factors that may raise these estimates somewhat, although ignition of live vegetation is not likely (Bush and Small, 1987). It has also been suggested that direct production of soot could result from the gasification (pyrolosis) of organic matter by the thermal radiation from the nuclear fireballs. Gostintsev et al. (1986) and Golitsyn (1986a, 1986b) suggest that as much as 20 Tg of elemental carbon could be generated by this process, but this is highly uncertain. If this were to happen and if the resulting soot were lofted into the stratosphere by the rising mushroom clouds, this process alone could cause significant climatic effects.

2.2 Smoke Emission Factors

The amount of smoke that is emitted depends strongly on the nature of the material and the conditions of the combustion, particularly the ventilation of the fire. In general, wood gives off less smoke than petroleum and polymeric materials and the smoke may be less absorbing. The fraction of the fuel that is transformed into smoke tends to increase as oxygen availability is reduced, so wood in urban areas could be an important contributor to soot emissions if ventilation is limited. On the other hand, if the fires are freely ventilated, the smoke emission factor would be only about 10% of the values used in initial assessments (Williamson et al., 1986).

A number of groups have measured the smoke yield from a wide variety of substances under laboratory-scale fire conditions. Although it is not at all certain that such experiments adequately represent the type of combustion that would take place in large fires ignited by nuclear explosions (e.g., the radiant fluxes are much lower and the flame height is much smaller), interesting insight has been obtained. An example of the results from such laboratory studies can be found in Andronova et al. (1986), for which the smoke yield was 1.5% for fresh wood and 4.0% for dry wood (the higher the water content of the wood, the smaller the fractional yield). For plastics, smoke yields ranged up to 11%. Other investigators have found significantly smaller values if the fires are freely ventilated, and similar values (~3%) for poorly ventilated fires (Mulholland, 1986; Patterson et al., 1986).

The material actually consumed in urban fires would be a mixture of substances. Andronova et al. (1986) found that a mixture of substances labeled "city mix," composed of 60% wood, 20% paper, 15% fabrics, and 5% plastics (which may be a low estimate of plastics for many modern cities) had a smoke yield of 5-6%. Burning of petroleum stocks would also generate large amounts of black smoke, with emission factors ranging from 3–4% in relatively small fires (Andronova et al., 1986) to 10% or more in very large fires (Zak, 1987). These results are in general agreement with the data reviewed by Penner (1986a) and are about 50% higher than the estimates used in NRC (1985).

Field programs are being planned in order to measure smoke yield in real fires. One type of experiment will be based on planned forest burnings for which the source amount can be measured in advance and large areas can be ignited nearly simultaneously. A second type of experiment will measure the emissions from large oil pool fires (usually set for other purposes). Although these fires will be much smaller than those that could result from a nuclear war, they will help serve to assess the validity of scaling laws being applied to the results from laboratory-scale fires.

2.3 Smoke Optical Properties

The optical properties of the emitted smoke are critical to determination of its climatic effects. These properties are dependent on the size, structure, and composition of the smoke particles. The optical properties of the smoke particles are usually expressed in terms of the specific extinction and absorption coefficients, k_e and k_a, in units of m^2/g. The ratio $(k_e - k_a)/k_e$ is called the single scatter albedo ω, and the difference $k_e - k_a$ is the specific scattering coefficient k_s. In addition to the extinction and absorption coefficients, the mean cosine of the scattering angle, which characterizes the phase function of the scattering and depends on the complex index of refraction and the aerosol size distribution. is necessary to calculate the effect of the smoke on radiation transfer. When the specific extinction (absorption) coefficient is multiplied by the atmospheric smoke loading (in g/m^2), the result is called the extinction (absorption) optical depth. A convenient way for comparing different smoke loadings is to calculate the value for the hemispheric average of the absorption optical depth, that is, the absorption optical depth assuming uniform distribution of the smoke over the hemisphere.

The specific extinction and absorption coefficients are a function of the type of material burned, the size and structure of the particles, the wavelength of the light and other factors. Smoke from the burning of petroleum products and polymers may have a higher specific absorption coefficient than wood smoke and should therefore be accounted for separately. Measurements of the specific extinction coefficient for the "city mix" described above suggest a value of about 6 m^2/g, which is only slightly higher than the NRC (1985) value of 5.5 m^2/g, and a value of ω of 0.65 (close to the NRC value). For petroleum, the corresponding figures are 10 m^2/g and 0.3, indicating its highly absorbing characteristics. Smoke from some plastics can also be highly absorbing, which is a result of the high value of the imaginary index of refraction (order unity) and the fractal character of the smoke (Pittock et al., 1986; Penner and Porch, 1987). For the smoke resulting from urban and petroleum fires, the SCOPE-ENUWAR project is now suggesting use of a specific extinction coefficient of 10 m^2/g and single scatter albedo of 0.5 at a wavelength of 0.55 μm, which makes the smoke about twice as absorbing as the NRC (1985) baseline assumption. They are also suggesting that these optical properties be used independent of particle size because branch-chained smoke particles with fractal dimension less than 2 cannot be approximated as spherical particles when calculating optical properties (Berry and Percival, 1986). However, it remains to be tested whether the smoke particles would maintain their small fractal dimension when coagulation occurs in highly dense plumes or when particles are processed by clouds.

It is also important to estimate the optical properties in the thermal infrared. Typically, the specific extinction coefficient in the infrared (equal to the specific absorption coefficient because particle sizes are in the Rayleigh limit for infrared wavelengths) has been assumed to be 10% of the specific extinction coefficient in the visible (e.g., NRC, 1985; Pittock et al., 1986). Data from Andronova et al. (1986) suggest that this may be an overestimate by a factor of 3 for real smoke particles (as opposed to the spherical particles used for the theoretical estimate). The wavelength dependence for extinction found in these experiments suggests that there is a bimodal size distribution, with modal particle radii centered at less than 0.03 μm and at about 0.2–0.3 μm (as a result of the chained structure). The smaller mode is consistent with electron microscope measurements by Clarke and Papanayotou (1986), who found that the smoke particles consist of spherules about 0.05 μm in diameter. The experimental measurements by Andronova et al. (1986) also indicate that for some materials the specific extinction coefficient in the infrared is only about 1–5% of the specific extinction coefficient in the visible (i.e., values from less than 0.1 to about 0.5 m^2/g). Such a value would tend to increase upper atmospheric temperatures, and reduce surface temperatures by a few degrees. However, measurements of acetylene smoke particles by Roessler and Faxvog (1980) and of diesel fuel smoke by Bruce and Richardson (1983) found values of 1 m^2/g at 10 μm, which would tend to have the opposite effect.

Another important point has been raised by Slingo and Goldsmith (1985), who pointed out that about half of the solar energy is in the near infrared. At these wavelengths, the particles usually have a smaller extinction coefficient than in the visible, which would tend to ameliorate the radiative perturbation. A broader set of spectral measurements, including measurements of smoke emerging from large, experimental fire plumes, will be needed to help resolve the differences that have been found in laboratory experiments and to provide the basis for more accurate treatment of radiative effects.

2.4 Total Smoke Production

The amount and properties of the smoke generated by a nuclear war are based on the product of a set of rather uncertain numbers. As an example, if we assume that one-fourth of the approximately 10000 Tg of wood are burned with a smoke yield of 2% and a specific absorption coefficient of 2.5 m^2/g, the resulting hemispheric average absorption optical depth (HAAOD) would be about 0.5. Burning 75% of the approximately 1400 Tg of petroleum-based products with an emission fraction of 7% and using an absorption coefficient of 5 m^2/g would give a HAAOD of about 1.4. Both of these numbers are before taking into account prompt or early time scavenging, which is usually done before providing an estimate for use in climate simulations. Penner (1986a) has reviewed the estimates for these various numbers and (adjusting her numbers to remove inclusion of the scavenging factor and assuming spread over the full hemispheric area) suggests that a plausible range for HAAOD is from about 0.4 to 3.0 if both the wood and petroleum-based fuels are burned. Turco et al. (1987) argue that the upper limit may range to about 10, although this estimate assumes upper limit emission factors and that 75% of the upper limits of combustible fuel in the NATO-Warsaw Pact countries would burn in flaming combustion. The extinction optical depth would be higher by a factor $(1-\omega)^{-1}$. The many assumptions and various experimental and modelling results mean that the range of possible values in total smoke production remains large and this continues to be a major contributor to the ranges in the projected climate perturbations.

2.5 Conclusions

Available scientific information shows that a major nuclear exchange could ignite fires that would inject tens to hundreds of teragrams (millions of tonne) of dark smoke into the atmosphere. The optical properties of the smoke would be strongly dependent upon the amount of petroleum, artificial polymers and related products burned. Uncertainties in these estimates are large and very dependent on the war scenario chosen, so that the possibility of larger or smaller atmospheric smoke concentrations cannot be ruled out. Using what appear to be plausible estimates, the initial hemispheric average absorption optical depth of the smoke could range from a few tenths to ten times as much, in the absence of prompt and early time scavenging and assuming spread over a hemisphere. Uncertainties in this estimate are large and will be difficult to narrow because of the dependence on fire conditions, which are poorly understood at present; however, the plausibility of large injections cannot be ruled out.

3. THE FIRST FEW DAYS

Poorly understood and under-studied processes govern the transition of smoke particles from their generation in the fires to their spreading to scales which can begin to affect the global weather and climate. Rising from the fires, the size distribution of the smoke particles may be altered by coagulation. Adiabatic expansion of the rising fire plume leads to cooling and then condensation, involving both the boundary layer water that is drawn into the plume and the water given off as a combustion product. Depending upon their chemical and geometric characteristics, the particles may serve as condensation nuclei for cloud droplets or ice particles, be incorporated into water droplets in precipitation and scavenging processes, emerge from the cloud after having been transformed by cloud processes, or simply pass through the cloud. The extent of condensation, which depends on fire intensity, local meteorology, and other factors, determines whether precipitation occurs and whether the captured particles that have been scavenged by the cloud drops are carried to the ground (this process is referred to as prompt removal) or are released back to the atmosphere, perhaps in a more compact form than when first captured, as the rain drops or ice particles evaporate. During the first few days as fire plumes spread, merge, and experience the prevailing meteorological environment, early removal may occur, coagulation may continue to alter the size distribution, solar heating may warm and loft the smoke upward, or nighttime infrared cooling may lead to some subsidence of the smoke layer. It is this complex of processes that determines the amount and characteristics of the smoke that is injected to global scales.

There has not yet been a comprehensive treatment of this set of processes. Turco et al. (1983) simply assumed that about half of the initial smoke particles would be removed from the atmosphere through these processes. The NRC(1985) report baseline case assumed a similar fraction, but indicated that the possible range extended from 10 to 90%, providing little basis for even these weak limits. Neither group assumed that the many possible processes would alter the size distribution of the particles.

3.1 Prompt scavenging and removal

Over the past few years, several groups have modified cloud models to study the plume that would be created over variously sized urban fires. Initial estimates from Cotton (1985) suggested that, in an intense fire plume 30 to 60 minutes old, less than 2% of the smoke would have been captured in rain drops (he accounted only for phoretic processes as a scavenging mechanism); when Tripoli (1986) allowed smoke particles to serve as condensation nuclei (assuming, perhaps unrealistically that all particles would be hygroscopic), the fraction increased to more than 80% In the latest calculations of the Colorado State group, which account for the evaporation of water drops as ice forms (in their mechanism ice attracts water away from the rain drops), the fraction scavenged in their baseline case has now dropped to less than 20%. In a simulation of an urban area fire in San Jose, California, Tripoli and Kang (1987) found less than 10% removal by prompt scavenging. Studies by Bradley (1986, 1987) and Bacon et al. (1987) however, suggest that a much larger fraction may be scavenged in the plumes of intense fires. In Bradley's model, this occurs because of the absence of the ice phase and lack of an overseeding mechanism, but in Bacon's model, his use of Oroville's mechanism (Lin et al., 1983) for treating ice phase physics, which includes riming (i.e., capture of water droplets by falling ice particles) as well as the ice nucleation treated by Tripoli, leads to scavenging of half (assuming hydrophobic) to virtually all of the hygroscopic smoke particles that were assumed to serve as condensation nuclei. The results of these calculations to estimate scavenging thus cover a broad range (i.e., 10 to 90%), and none of the models yet represent all of the important cloud processes nor have they reported complete results for particle scavenging (i.e., the fraction of particles taken up in a hydrometeor at some stage) and removal (i.e., particle deposition at the surface). All of the cloud models also currently available greatly simplify the treatment of droplet and ice size distributions. The nucleation process may be affected by the more intense vertical motions, by the higher supersaturation that may occur in the intense fire plume (Penner and Edwards, 1986), and by the chain-like character of coagulated smoke particles. Some suggest that electrical effects may increase the efficiency of capture processes, but quantitative studies have not been done. The presence of dust, debris, and other particulate matter may also alter coagulation and precipitation processes (Porch et al. 1986) and there are certainly additional processes that may need to be considered before accurate estimates of scavenging and removal can be made.

Because fires observed in the past have not been nearly as large or intense as postulated post-nuclear urban fires would be, observational studies provide only limited guidance. The very large Tillamook forest fire in Oregon in 1933 (with a plume reaching to 13 km), the Chapleau, Canada controlled forest fire in 1985, and other similar fires are not reported to have generated any rain; that is, there was no net removal of smoke particles, even though incorporation of particles into water droplets and subsequent evaporation may have occurred. The rain following the Hiroshima explosion and fire, however, created a "black rain" that removed smoke particles. Because very limited data exist on the fraction of aerosol removed by natural systems, it is tempting to try to relate the fraction removed to the fraction of water removed in natural systems. For example, natural convective cloud systems are thought to precipitate out only a fraction (perhaps a quarter) of the condensed water, but some unusual situations, for example steady orographically-forced systems, may remove as much as 90%: the range of possible values, therefore, remains broad.

Laboratory experiments are being conducted to investigate whether the smoke particles may serve as cloud condensation nuclei (CCN). For fresh smoke particles made by the burning of various pure substances, it has been thought that they would not serve as condensation nuclei (Charlson and Ogren, 1982). Experiments supporting this finding, however, often involve smoke that has been diluted to inhibit further coagulation during the measurement process. Penner (1986b) describes data which support the notion that highly carbonaceous particles that were originally thought to be hydrophobic can act as CCN and that this would be evident if dilution were not used to stop coagulation. Furthermore, many of the experimental results are consistent with the interpretation that it is primarily the larger particles which are acting as CCN. Her analysis (which assumes spherical particles) indicates that particles as small as 0.1 μm in radius would be incorporated into the cloud by nucleation if supersaturation reached $\sim$1%. This thesis needs to be experimentally verified, however, in part because small particles could also act as CCN if they contained a hygroscopic component.

Based on the few simulations, laboratory studies, and analyses of actual fires that have been done, the extent of prompt scavenging in the fire plume remains highly uncertain, especially given the many simplifications, assumptions, and omissions in present models.

3.2 Effects of plume and cloud processes on the radiative properties of smoke particles

Laboratory studies suggest that, for many substances, the initial smoke emissions consist of very small (of order 0.05 μm), highly carbonaceous spherules which aggregate to form multi-branched, low density, chained particles having fractal dimension less than 2 (Berry and Percival, 1986) and specific absorption coefficients of as much as 10 m^2/g (rather than the value of 2 m^2/g assumed in many earlier studies). Such fluffy aggregates, whose elemental carbon content can be high, often have specific absorption coefficients similar to those of the small spherules of which they are formed, rather than those of a spherical particle of the same total mass. Whether these structures can survive the turbulent fire plume environment and cloud processes is an important unknown issue, introducing perhaps a factor of two uncertainty into estimates of the optical properties of smoke emerging from a fire plume.

3.3 Altitude of smoke injection

Observational evidence suggests that smoke from localized forest fires usually rises to 2-3 km, whereas smoke from larger fires with good ventilation and humid air has been observed to reach 5-6 km (e.g., the Chapleau, Ontario fire of August 3, 1985). Plumes from very large forest fires (e.g., Tillamook) and urban fires during World War II reached heights of 10 km or more. In view of these results, it seems likely that much of the smoke would be carried into the middle troposphere and some fraction may even reach the lower stratosphere.

Modified cloud models have been used to estimate plume injection heights for a range of fire intensities and meteorological conditions. These models suggest that very intense fire plumes may be able to loft smoke into the lower stratosphere, but for most of the fires, which would be of moderate intensity, the top of the plume above the fire may be limited to the middle troposphere or perhaps up to the tropopause. Vorticity may lead to creation of a vortex which may affect plume rise. It was originally thought that vortex formation (firestorms) may enhance plume rise (e.g., Turco et al., 1983), but Tripoli and Kang (1987) show a case in which plume rise was limited by formation of a vortex in the later stages of fires. Wind shear may moderate the rise or reduce the subsidence of the plume from its peak height over a fire. The models suggest that the total heat release (the power) of the fire, more than a fire's areal extent, control the height of injection (Small et al., 1987). Meteorological conditions are also important, the significant factors being atmospheric stability and the availability of moisture to contribute latent heat. Further review of the issues related to plume rise can be found in Pittock et al. (1986) and Budyko et al. (1986).

There have been no statistical compilations to estimate the collective result of thousands of fire plumes of varying intensity and duration under a representative variety of meteorological conditions. As a result, a variety of assumptions have been made concerning the appropriate vertical distribution for initializing climate impact simulations. Turco et al. (1983) assumed a variety of smoke distributions with many of the cases leading to substantial injections into the upper troposphere and as much as 5% spillover into the stratosphere. NRC (1985) used a constant smoke density (g/m^3) from the surface up to 9 km. Several of the global climate simulations have assumed a constant smoke mixing ratio (g/g) from the surface up to an altitude of 7 to 11 km. These 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 in which solar absorption occurs, and the less effective the containment of longwave radiation by the greenhouse effect. As fire plume models improve, estimation of injection altitude needs to be an area of continued study.

3.4 The first few hours

There has been little study of phenomena that would occur in the first few hours after plume injection. The cloud models suggest that 100 to 1000 times as much water as smoke may be lofted into the upper troposphere (Tripoli, 1987), almost certainly creating clouds that would cap the fire plume. Some of the water may contribute to ice particle formation, leading perhaps to extensive cirrus anvils of highly absorbing smoke-ice particles. The radiative effects of such clouds, water vapor, and smoke-ice particles are unknown but may be important. Solar absorption by smoke particles could warm the upper cloud layer and create instability. A model study by Demchenko and Ginsburg (1986) showed that the rate of ascent due to this mechanism could be of the order of 1 km/day, at least for the initial smoke densities. During the night, the whole layer could be cooled because of the extensive anvil of ice particles (Tripoli, 1987). Such cooling could cause subsidence, consequent adiabatic warming, and drying. The net diurnal effect would likely be lofting, considering the specific values of the infrared and visible radiative parameters of the smoke (Malone, 1987), but these processes deserve much more study.

3.5 The first few days

The injection of smoke and water would take place in an initially active mesoscale environment which would include pre-existing fronts and circulations. As the individual smoke plumes spread and then merged with other plumes, the radiation balance would start to be strongly modified, causing cooling at the surface and warming aloft that would restrict vertical mixing and convection. Molenkamp (1986) has studied the onset of surface cooling in a coastal environment and finds relatively rapid surface cooling down to the dew point followed by progressive development of a deepening fog layer as a result of a continuing inflow of moisture from an upwind ocean area. Starting with a smoke cloud having an initial diameter of 150 km, Golding et al. (1986) studied the evolution of the cloud over a 12 hour period over central England on a typical day in May. The differential heating of the smoke-containing air induced secondary circulations with vertical velocities of the order of 0.2 m/s, causing some condensation to occur over about one-fifth of the smoke-covered area. The model did not treat smoke particles as CCN or calculate smoke scavenging, but the relative areas of the smoke and the rain suggest that removal would be modest, although the amount of air processed would exceed the area of condensation.

Quite clearly, there needs to be much more study of these processes; existing mesoscale models provide an initial capability, but more detailed treatments of radiation and aerosol and cloud physics must be included.

3.6 Interface between field studies and models

Field studies of the plumes from large fires (including planned forest and oil pool fires and inadvertent fires) should provide some data for testing models and parameterizations, but significant problems will remain in scaling the total power of the fires upward by two to three orders of magnitude from the relatively low-intensity fires that can be instrumented. Laboratory and cloud chamber experiments can also provide useful information, but again the limitations of such studies must be recognized. Given these difficulties, the recent variations in the estimated amount of smoke which would survive prompt scavenging and removal during the first few days were to be expected.

3.7 Conclusions

In the first few days after injection, the smoke particles would be affected by transformation and scavenging. Important progress has been made in modeling of fire plumes and study of the microphysical properties of smoke particles, but much remains to be done. If about half of the smoke is assumed to be removed by prompt scavenging, sufficient amounts of smoke would remain to create hemispheric average absorption optical depths ranging from a few tenths to ten times as much. Too little is known about aging, coagulation, and transformation processes on these scales to provide definitive guidance on the physical characteristics of the particles that would govern long-time survival of the particles in the atmosphere, but the particles seem likely to be strong absorbers of solar radiation.

4. ATMOSPHERIC PERTURBATIONS DURING THE FIRST MONTH

The one-dimensional calculations by Turco et al. (1983) provided a preliminary indication that the climatic effects could be significant. They were followed very quickly by two-dimensional (MacCracken, 1983) and three-dimensional calculations (Aleksandrov and Stenchikov, 1983, 1984; Covey et al., 1984). Since these initial studies, significant progress has been made in estimating the potential smoke-induced perturbations to the atmosphere over the first several weeks following a nuclear war. The earliest calculations typically assumed fixed smoke extent and amount, 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 infrared. The most recent calculations have attempted to correct these initial simplifications, but they continue to suffer from many approximations and limitations. For example, the boundary layer is poorly resolved, few calculations have been carried to beyond a month, the evolution of particle size and scavenging are poorly treated, ocean temperatures are often held fixed, and interactive atmospheric chemistry has yet to be introduced. In addition, the models do not treat the early time processes occurring during the first few days, assuming that the smoke has already experienced prompt and early-time scavenging and has spread to cover sub-continental to continental scale areas.

4.1 Model calculations

Four groups have carried out most of the three-dimensional climate perturbation studies. They have generally used variants of two different general circulation models (GCM): the National Center for Atmospheric Research (NCAR) and the Los Alamos National Laboratory (LANL) have used variants of the Community Climate Model (CCM); the Lawrence Livermore National Laboratory (LLNL) and Computing Centre of the USSR Academy of Sciences have used variants of the Oregon State University tropospheric GCM. The United Kingdom Meteorological Office GCM has also recently been used to test the validity of some of the assumptions in the original CCM calculations (Mitchell, 1987), but a comprehensive calculation has not yet been done. The general similarity of simulation results from the various models suggests that differences in vertical and horizontal representations are relatively unimportant determinants of the large-scale character of the perturbations, at least during the initial acute phase lasting one to two weeks. For example, in comparative tests with the NCAR and LLNL models, the average surface air and ground temperature decreases for mid-latitude land areas were within about 15% of each other, assuming the same smoke injections and turning off transformation and removal mechanisms.

The initial interpretation of the Turco et al. (1983) results portrayed the perturbation from a global-scale war involving urban areas as being a rapid decrease of mid-latitude land-surface temperatures to well below freezing, a "nuclear winter", with the possibility of freezing conditions even in low latitudes, and in some less careful presentations, over the entire globe. These results were based on calculations with a one-dimensional radiative-convective model that represented only annual and global average conditions and accounted for ocean buffering empirically (based on climate observations). The effects of cloud, circulation, and other feedbacks and smoke spread could not be treated directly.

The early three-dimensional calculations (see Golitsyn and Phillips, 1986) with uniformly spread smoke moderated the initial prediction of deep freezing conditions by more accurately representing the stabilizing effect of ocean temperatures, which were held fixed at their climatological values. These simulations also found that the effects of smoke would be largest during the warm season and least during the cold season of the year.

The latest series of calculations includes, although not always in the same model, treatment of the transport and dispersion of the smoke, coupling of smoke removal to model-predicted precipitation, varying particle size, coagulation, diurnal variation and scattering of solar radiation, and absorption and emission of thermal radiation by smoke particles. The treatment of the surface boundary layer is still inadequate, however. Also, computations are only starting to account for seasonal dependence (e.g., the varying ocean temperatures). In addition, shortcomings remain in the representations of various processes (e.g., particle scavenging, for which few, if any, analogs exist). Smoke transport is now carried out by a variety of techniques (Eulerian schemes involving finite difference, finite element, or spectral representations and a Lagrangian particle approach). On the global scale, Malone (1987) has demonstrated that the Eulerian techniques are too dispersive by comparing model calculations to observations of the spread of a deuterated methane (CD_4) tracer release near Antarctica. Other processes (e.g., atmospheric chemistry and chemical scavenging) have not yet been treated at all. Nonetheless, the available model simulation results do provide the best scientific basis for estimating the global-scale atmospheric response to a massive smoke injection.

The baseline smoke injection for GCM simulations has typically involved global injection of 150–200 Tg of smoke with a specific absorption of 2–2.5 m^2/g, corresponding to a hemispheric average absorption optical depth of 1 to 2, with variations extending the range by a factor of about 3 about the baseline. As indicated in earlier sections, the latest results suggest that the mass of smoke injected could be less, but the specific absorption coefficient would be greater; fortuitously, the two effects approximately balance in terms of hemispheric average absorption optical depth.

The initial response of land temperatures to an overlying smoke layer corresponding to a smoke layer having hemispheric average absorption optical depth of order unity would be a rapid decrease in temperature, much like a prolonged night-time cooling. Under a dense smoke layer and in mid-latitude continental interiors, the calculated temperature drop could be 20–30°C during the first few days. The GCMs produce a more rapid cooling than occurred in the Turco et al. (1983) computation because their surface temperature, as in the real atmosphere, is not directly coupled to the lowest atmospheric layer, as is often assumed in radiative-convective models. It is thought, however, that this sharp cooling would initially be limited at the dew point by fog formation in the first few days (Knox, 1983a; Molenkamp, 1986), which is a process not now treated in general circulation models. The persistence of the fog effect is not known and would depend upon local meteorological conditions, the availability of nearby water bodies as a source of moisture, ice particle formation and removal, and other factors.

Over approximately the first two weeks following a summertime injection, the models estimate that northern hemisphere mid-latitude mean land surface temperature would decrease by up to 15 to 20°C. Temperature decreases in continental interiors could be up to double the average value, producing occasional occurrences in some models of sub-freezing conditions or frost. Temperature changes in coastal regions would be more modest and average temperature would generally stay well above freezing, although occasional frost events are calculated in some models as continental air masses move across. Ground temperature would decrease by several degrees more than air temperatures, creating a very strong radiative inversion near the surface. [In comparing published estimates of model response, it is important to note that the NCAR group has generally reported the change in ground temperature whereas other groups have generally reported changes in surface air temperature. This can cause differences in the estimates of 3–4°C. In the Turco et al. model, ground and air temperatures are coupled so that the two temperature decreases are the same.] The inability to simulate fog formation may allow excessive cooling while the inability to resolve the very sharp surface inversions (Pittock and Garratt, 1987; Ghan et al.,1987a) and drainage flows may lead to an underestimation of the coldest events. Until results are available from simulations with improved representations of the boundary layer, the possibility of widespread frost and severe chilling remains significant, especially in the early and late parts of the growing season. Either condition would threaten mid-latitude agriculture. On the other hand, conditions with prolonged temperatures well below freezing—as nuclear winter was often first portrayed—are almost certainly ruled out, even in mid-latitude interiors, given the baseline smoke injections. For larger or springtime smoke injections, however, the frequency and extent of subfreezing conditions could increase.

As the smoke spreads out over the northern hemisphere and is subjected to removal by precipitation and chemical destruction, the acute temperature decreases in the mid-latitude continental interiors would moderate (to about a 5 to 10°C perturbation), while sub-tropical land areas would begin to be affected. The recent studies suggest that, for baseline smoke injections, the temperatures in India and southern China could be 5 to 10°C below their normal summertime values, with little likelihood of frost and few occurrences of below 15°C temperatures, a threshold which is thought to be important at a sensitive stage of rice growth. The sub-tropical region would generally be affected mainly by circulation changes; e.g., the induced subsidence along the southern edge of the smoke cloud could reduce cloudiness and even cause a local temperature rise. Only very modest temperature decreases are thought to be possible in the tropics or in the southern hemisphere during the first few weeks following smoke injection, except for extreme smoke injection scenarios for which a temperature drop of the order of 5°C may be expected.

On the other hand, induced changes in precipitation would perhaps be more significant than the temperature changes for agriculture in low latitudes. Smoke-induced upper tropospheric warming and the surface cooling could shut off convective precipitation over much of the northern hemisphere land areas, thereby disrupting the summer monsoon. This idea was suggested by Obouhkov and Golitsyn (1983) and now is found in the results of simulations described by Ghan et al. (1985, 1987a) and Thompson et al. (1987). These precipitation changes appear to be much less dependent on smoke amount than are the surface temperature reductions. Even for smoke injections as small as 15 to 50 Tg (equivalent to a hemispheric average absorption optical depth of a few tenths), for which mid-latitude land temperatures would not drop more than 5 to 10°C during the first few weeks, a substantial reduction in precipitation and disruption of the summer monsoon would result. Precipitation changes in coastal areas are less certain; although convection is shut off over land, the relatively warm ocean temperature could continue to cause rapid warming of cold continental air masses.

Although the temperature and precipitation perturbations would be relatively little affected by smoke scavenging and aging during the first few weeks, events during this period would determine the amount, distribution and characteristics of the smoke available to induce the longer-term effects discussed in the next section. The solar warming of the smoke, especially during the warm season, would cause large-scale, upward lifting of the smoke from tropospheric to stratospheric altitudes where the residence time of the smoke may be months to years. In addition, solar absorption by the smoke particles tends to warm the atmosphere, increasing stratospheric stability and perhaps lowering the tropopause (Malone et al., 1986). Model calculations indicate that the fraction of the smoke that would be lofted increases with the smoke amount. For baseline smoke injections, about one-third to one-half may be lofted to stratospheric altitudes. This lofting may be limited if dust injected by surface bursts overlies and screens the smoke layer from solar radiation and the fraction of smoke lofted (but not the mass) may decrease for very large smoke amounts. The reduction in precipitation would also tend to extend the smoke lifetime. The particle size distribution may also evolve during the first few weeks.

Many of these effects were perceived in the early analyses, as discussed in Golitsyn and Phillips (1986). Although the recent calculations have refined the results considerably, they have not altered the nature of the basic findings. Furthermore, the plausibility of significant temperature reductions over the first few weeks in mid-latitudes and significant precipitation reductions over most northern hemisphere land areas, including suppression of the summer monsoon, is now more firmly established.

4.2 Study of partial analog perturbations

Over the past few years, there has been an increased effort to analyze various geophysical events in search of confirmation that aerosol injections can affect the temperature. Several cases involving large injections of dust have been studied, even though dust is mainly a scatterer of solar radiation rather than an absorber, as is the case for smoke.

In addition to use of Martian dust storms as an analog (see Turco et al., 1983; Golitsyn and Phillips, 1986), terrestrial dust storms provide some useful insights. Saharan dust storms play a role in the climate of the desert and regions to the west to which the trade winds transport millions of tonnes of dust, often reaching the American continent. Kondratyev et al. (1971) observed an appreciable absorption of solar radiation by desert aerosol. Xu et al. (1979) reported a quick temperature drop of 10°C after arrival of an intense dust storm in western China. Brinkman and McGregor (1983) described a temperature decrease of several degrees and a reduction in total solar radiation at the surface of 20–30% when winds brought large concentrations of dust from the Sahara to Nigeria. About fifty cases of dust storms and heavy dust haze have recently been considered by Golitsyn and Shukurov (1987). They analyzed temperature records from five meteorological stations in south-west Tadjikistan. During these events, visibility ranged from 50 m to several kilometres and the thickness of the dust layers ranged from 1 to 2.5 km. The comparison of diurnal temperature course on dusty days with that on preceding and subsequent clear days showed a nighttime warming by a few degrees and a considerably larger cooling, up to 10–12°C, during daylight hours. The warming was evidently due to the increased IR opacity at night and the cooling to decreased solar radiation reaching the surface during the day. Overall, the changes were found to depend strongly on the visibility (i.e., dust concentration).

The study of smoke injections from large forest fires has indicated an effect on near-surface temperatures, even though the smoke from such fires is not as highly absorbing as urban smoke and its relatively low injection altitude tends to have much lesser effects on net radiation than would the smoke from post-nuclear fires. The effects of several large American forest fires are described in the NRC (1985) report. Although the smoke from a very intense fire in Oregon in August 1933 reached a height of 13 km, the altitude of smoke plumes from medium size forest fires is typically several kilometres (see Golitsyn and Phillips, 1986; Budyko et al., 1986). The best documented fire is the large Alberta fire of September 1950 (see NRC 1985 and references cited therein). The smoke traveled across Canada and the United States and then over the Atlantic and on to western Europe, causing light obscuration over a large part of the North American continent that reduced maximum temperatures by several degrees, and causing unusual optical effects in England (blue moon and sun). This smoke was located mainly in the middle troposphere, at least over the United States, but it extended up to the tropopause over England.

Robock (1987) has compared model-forecast temperatures with observations in several cases where forest fire smoke moved into a region. In each of these cases he has found a reduction in maximum temperatures of 1–4°C, depending on the thickness and altitude of the smoke layer.

Large peat bog and forest fires occurred in many locations in the European part of the USSR during August 1972. An analysis of the meteorological situation was done by Abakoumova et al. (1986) and of the optical properties by Sokolik et al. (1986). The analysis revealed that the extinction optical depths were in the range 0.5–1.2, with the single scattering albedo of the particles being 0.3 to 0.9. These numbers agree well with direct measurements of forest fire smoke under laboratory and natural conditions (e.g., Pittock et al., 1986). A diurnal heating of 1.4 ± 0.9°C during the day was induced in cases with smoke in the lowest two to four kilometres (Veltishchev et al., 1987), which agrees with earlier model results (Cess et al., 1985) that moderate amounts of low level smoke can cause a small warming of the surface.

The Great Siberian fires of 1915 were considered by Ginsburg and Golitsyn (1986) and then by Veltishchev et al. (1987). They estimated that 30 ± 10 Tg of smoke were generated by the fires during a period of about 50 days. Assuming a mean lifetime of one week and an area covered by smoke of $5\text{–}6 \cdot 10^6$ km^2, the extinction optical depth would be 3 ± 1. Analysis of daily temperature records at several Siberian stations together with a "dry fog" index (a measure of the intensity of smoke) revealed a statistically significant temperature decrease of several degrees, correlating well with the smoke intensity. The radiative-convective model of Veltishchev et al. (1987) gives results for these three cases which agree satisfactorily with observations.

All of these examples with dust and forest smoke show that aerosols can influence the surface temperature. These cases also can be used to validate global or regional models which are, or could be, used to study the problems under discussion in this report. These analog studies have found no inconsistencies with calculations made with general circulation models and may serve as a partial validation for models used to study the consequences or larger smoke injections. There are, however, substantial differences between many features of the analogs studied to date and of a potential post-nuclear smoke injection; the continued study of a wider range of analogs may therefore prove helpful in providing further insights.

4.3 Conclusions

Injection of large amounts of highly-absorbing smoke into the atmosphere would lead to global-scale perturbations. During the first month, the sunlight reaching the surface in northern hemisphere mid-latitudes could be reduced by 80% or more, resulting in zonal mean land summer temperatures up to 15 to 20°C below normal for up to a few weeks after injection of the smoke. Changes could be 15 to 30°C in continental interiors, but would be less in coastal areas. The studies of the climatic impact of a baseline summertime smoke injection, conducted with three-dimensional atmospheric circulation models and comprehensive representations of physical processes, indicate mean land temperatures at or slightly above the freezing level with transient regional episodes of sub-freezing temperatures, which is a mitigation of the intense freezing conditions suggested by early results with atmospheric models containing important simplifications. On the other hand, these recent studies emphasize the plausibility of a serious reduction of precipitation over continents and a disruption of the summer monsoon, even with substantially less than the baseline smoke injection. Finally, the expectation of stratospheric transport of smoke into the southern hemisphere during the first month has been generally confirmed for sufficiently large smoke injections.

5. ATMOSPHERIC PERTURBATIONS BEYOND ONE MONTH

Initial calculations for times beyond a month have been done using an energy balance model (Robock, 1984) or with fixed smoke extent (Aleksandrov and Stenchikov, 1984; Covey, 1987; Pittock et al., 1987). A few studies have begun to examine the potential atmospheric effects beyond the first weeks using interactive smoke-atmosphere-ocean models (Stenchikov and Carl, 1985; Stenchikov, 1986; Ghan et al., 1987b). The important additions in these computations are the treatment of ocean temperature and sea ice, two factors which are essential to consider in simulating the seasonal evolution of the climatic consequences of a nuclear war. So far, the results must be viewed as preliminary because there remain significant limitations in the treatment of the evolution of the smoke in the models. For example, little verification has been done of the assumed smoke removal mechanisms, no chemical interactions are permitted even though the large circulation and temperature changes would surely affect stratospheric ozone, chemical removal mechanisms of the smoke (which may be the factor limiting smoke lifetime) are not considered because they are still only poorly understood, the simultaneous effects of dust and nitrogen oxides are ignored, etc. In addition, the treatments of the ocean and sea ice are incomplete, e.g., the possible effect of deposited soot on sea ice albedo, as suggested in Ledley and Thompson (1986), is not taken into account. Thus, calculations on this longer time scale must be viewed as exploratory, serving as feasibility studies in advance of more complete simulations.

5.1 Effects of lofting, ocean mixing and sea ice

Three factors influencing the climatic response have so far been examined: smoke lofting, ocean cooling and changes in the extent of sea-ice. The intense solar warming of the upper part of the smoke cloud could produce strong upward motions that would loft smoke well into the stratosphere, where it could spread southward rapidly to cover at least the sunlit areas of the southern hemisphere (Malone et al., 1986). The lofted smoke fraction, which would add to the smoke already injected into the stratosphere by the most intense urban fire plumes (Cotton, 1985) and small-scale convection (Demchenko and Ginsburg, 1986), apparently increases with the total smoke injection (Malone et al., 1986; Ghan et al., 1987a). In the case of large smoke injections, up to about one half of the initial smoke mass is projected to remain in the atmosphere after a month, almost exclusively above the levels where it could be scavenged by precipitation. This would correspond to a global average absorption optical depth of a few tenths. The residence time of the smoke particles in the stably-stratified stratospheric layers would be controlled mainly by circulation patterns and would likely be six months or more, especially with the lowering and strengthening of the inversion at the tropopause that would be induced by the increased solar absorption due to the presence of smoke particles in the stratosphere. However, the chemical scavenging mechanisms which operate in the stratosphere are only beginning to be investigated (e.g., deHaas et al., 1986). Also, the added infrared opacity of smoke in the polar night may contribute to smoke removal by enhancing radiative cooling and the vertical overturning which now apparently serves to remove volcanic aerosols. Both processes would tend to limit the smoke lifetime.

For an absorption optical depth of a few tenths, radiative-convective models (Gostintsev et al., 1986; Golitsyn, 1986a, 1986b) suggest that the surface temperature reductions could be in the range of 5 to 10°C in interior continental areas. Pittock and Garratt (1987) used a horizontally compressed version of Pielke's sea breeze model (Mahrer and Pielke, 1977) having fine resolution of the surface boundary layer to derive a similar result. Reconciling these results with the GCM simulations, which provide poor vertical resolution but better treatment of horizontal heat fluxes from the ocean, is still to be done.

Similarly, the reduction of solar radiation reaching the surface could cause a hemispheric-average cooling of the ocean mixed-layer of the order of 1°C per month. The cooling would be stronger in the northern hemisphere where the smoke is thicker. Furthermore, increased or altered surface winds may increase the mechanical stirring of the ocean mixed-layer, causing entrainment of colder water into the thermocline. Mettlach et al. (1987) and Ganopolsky and Stenchikov (1987) suggest that this mechanism could lead to relatively rapid, localized cooling of the ocean's surface by a few degrees.

The changes in ocean and air temperatures would also allow an earlier formation of sea ice, an effect first studied by Robock (1984) using an energy balance climate model and more recently examined in GCM calculations by Covey (1987) and Ghan et al. (1987b). These studies all indicate that the earlier formation of sea ice would result in a prolonged cooling of northern hemisphere land areas by a few degrees and lasting through at least the first warm season following a spring or summer nuclear war. The possibility that smoke deposition could moderate or even change the sign of the sea ice feedback by reducing albedo (Ledley and Thompson, 1986) cannot be ruled out, although Robock (1984) suggested that new snowfall would quickly cover the soot.

5.2 Global calculations

Covey (1987) coupled the CCM to a mixed layer ocean model. He assumed an initial smoke amount equivalent to a hemispheric average absorption optical depth of about 1.5, but spread only over northern hemisphere midlatitudes and fixed in extent throughout the year-long calculation. After the first 30 days, he assumed that smoke would be removed with a 30 day half-life. Land temperatures dropped rapidly at early times to conditions colder than calculated by Robock (1984), but with rapid recovery, and even induced some warming as the smoke loading became small.

Pittock et al. (1987) used the Australian National Meteorological Research Center GCM and assumed a global average absorption optical depth of 0.2, based on estimates from Malone et al. (1986) of how much smoke might persist for months to a year following injection. They found 2–6°C cooling of land areas at 27°S. The Pittock and Garratt (1987) results with a mesoscale model suggest that accounting for infrared effects, which were ignored in the GCM calculation, would moderate these coolings by about 1°C. Pittock et al. (1987) also found significant disruption of the summer (January) monsoon precipitation in the Southern Hemisphere subtropics.

Ganopolsky and Stenchikov (1987) coupled their atmospheric GCM to a two-layer upper ocean model, but, unlike Covey (1987) and Pittock et al. (1987), allowed the smoke to be transported. They allowed smoke removal rates to be reduced by the atmospheric perturbation. Global ocean temperatures cooled about 1.2°C over the first month of the calculation due to wind-induced mixing of the upper mixed layer with the cooler thermocline. They found that localized cooling of up to 10°C was possible due to deepening of the mixed layer. Together with the thermal cooling, they found that mixed layer temperature was 1°C below normal after a year.

Ghan et al. (1987b) have coupled a two-level dynamical ocean model to the OSU GCM and are undertaking interactive simulations. They find that in response to an injection similar to the NRC (1985) urban baseline, ocean temperatures drop by about 5°C over the first few months in the 30–70°N latitude band, partly from mechanical mixing, but mainly from the dimunition of solar radiation. The model shows evidence of sea ice feedback (which extends the cooling) and hydrology feedbacks (which can lead to surface drying and subsequent warming of the land surface). The precipitation perturbation is significant only during the first several months, in part because their model does not isolate smoke in the stratosphere.

These calculations are identifying additional processes that must be treated. In some calculations, precipitation reductions at some locations lead to a drying of the land surfaces, thereby, in addition to stressing plant life, reducing evaporative cooling and causing a warming. At other locations, the increased stability of the troposphere reduces cloud cover (or leads to clouds that are optically thinner), which allows a greater fraction of the reduced solar radiation through to the surface. In all of the calculations, however, the perturbations are lasting from months to years after the massive injection of smoke and other substances.

5.3 Conclusions

As the smoke is dispersed and removed by atmospheric processes, climatic effects are expected to change from their initial acute phase response. Beyond one month, the large perturbation of northern hemisphere temperatures would be expected to decrease, although it is not known how rapidly. At the same time, for some scenarios the smoke would have spread over much of the earth, causing a reduction in sunlight of the order of 20% and a reduction of temperature of several degrees.

Only recently have calculations been extended out to a year or more. The results of some simulations suggest that spring and summer climatic conditions could be significantly affected in the year following the fires. The meteorological and physical uncertainties are such, however, that reliable quantitative conclusions regarding the effects of an injection of a specified amount of smoke in northern mid-latitudes cannot be reached beyond a few weeks in the northern hemisphere or, at later times, in the tropics and the southern hemisphere.

6. OTHER ATMOSPHERIC INJECTIONS BY NUCLEAR EXPLOSIONS

Nuclear explosions can cause the injection of a wide variety of substances into the atmosphere in addition to the smoke from fires. The explosions themselves produce radionuclides, cause chemical reactions that lead to injection of nitrogen oxides, and can loft large amounts of dust and other surface materials if they take place near the ground. The rising mushroom cloud can carry the materials and large amounts of water from the boundary layer well up into the atmosphere. The fires started by nuclear explosions would create gaseous products that can affect the radiative and chemical balance of the atmosphere when lofted by the flaming phase of the fire as well as air quality near the surface when given off in the smoldering phase. The fire plume and induced winds would also loft water vapor from the boundary layer and sweep material up from the surface. All of these products from the explosion and consequent fires must be considered in assessing the physical and atmospheric consequences of nuclear war. While most attention in recent years has been on smoke effects, it is important to recognize that other emissions could lead to important chemical, climatic, and physical consequences.

6.1 Dust

The amount of dust lofted into the atmosphere and the height of the injection would depend strongly on the assumed scenario, i.e., the number and yield of surface and near surface bursts. Although no new experimental evidence on dust injections has appeared during the last two years, there is an increasing understanding that such dust could play a substantial role in both the short- and long-term effects. The amount of sub-micron dust particles that could be injected could be several tens of teragrams (see e.g., NRC 1985, Pittock et al., 1986). If this dust were spread uniformly over the northern hemisphere, the resulting extinction optical depth could be about 0.5, which would cause a reduction of the total solar radiation flux at the surface by more than 10%. Because a substantial fraction of the dust would be in the stratosphere where its lifetime would be from months to years, the dust could contribute to large-scale temperature reductions of a few degrees due to the increase of the planetary albedo alone. If the optical properties of the dust, which are poorly known, were similar to typical continental aerosol (see WCP-55), absorption of solar radiation by the dust could also be an important consideration. If co-located with the smoke, the dust could tend to moderate the lofting of smoke, as discussed earlier in this report, by partially shielding the smoke from the solar radiation (Thompson et al., 1987). The spread of the dust in the stratospheric circulation must therefore also be treated in future calculations.

6.2 Chemical emissions

The shock wave and the intense heat of the fireball lead to the production of about 10^{32} molecules of nitric oxide (NO) per megaton of explosive yield (NAS, 1975; NRC, 1985). For very high altitude explosions (above 80 km), the production may be larger by a factor of about 5, according to Crutzen and Birks (1982). The introduction of nitrogen oxides could have two effects; namely, the absorption of solar radiation when present as nitrogen dioxide and the chemical destruction of stratospheric ozone (NAS, 1975; NRC, 1985; Pittock et al., 1986; Izrael and Karol, 1985). In the absence of other emissions and induced climatic changes, one-dimensional chemical kinetics models suggest that hemispheric average stratospheric ozone could be reduced by 20–40%; the ozone change and nitrogen dioxide increase would likely cause some climatic change, but the one-dimensional calculations done by Turco et al. (1983), MacCracken (1983) and Vupputuri (1986) suggest that this effect would be second order; Kondratyev and Nikolsky (1986) and Izrael et al. (1984) also suggest that the nitrogen dioxide could lead to cooling of only a few degrees (perhaps in addition to the smoke-induced cooling). Attempts to treat these effects in the context of the temperature and circulation perturbations brought on by the smoke injections (much less the heterogeneous chemical interaction of smoke and ozone) are still in their early stages. Initial analyses of the effects on reaction rates of temperature changes and changes in the solar radiation due to smoke and dust indicate that ozone destruction in the middle stratosphere could be enhanced by a factor of two (Izrael et al., 1984; Vupputuri, 1986). Additional destruction of ozone could occur as a result of dynamical changes (Pittock et al., 1986).

There are additional chemical interactions of the smoke with atmospheric constituents. Zvenigorodsky and Smyshlyayev (1985) suggest that the presence of smoke particles could reduce the concentrations of important radical species such as OH and HO_2 (see Gershenzon et al., 1987). Because these radicals act to convert nitrogen oxides to nitric acid, a decrease in their concentration would tend to maintain the high concentrations of nitrogen oxides, which could lead to enhancement of ozone destruction. This process may have caused the noticeable decrease in the stratospheric ozone concentration observed after the El Chichon and other volcanic eruptions. In addition, the effect of smoke particles on the concentrations of radical species could lead to less rapid scavenging of a variety of gaseous species.

Air quality in the lower troposphere could be perturbed both by the emissions from the fires (which remain near the surface if emitted during the smoldering phase) and by the altered atmospheric conditions. The emissions of direct concern include carbon monoxide and toxic compounds created in the fires (Birks, 1987). Of indirect concern would be the hydrocarbons and nitrogen oxides, which, under some circumstances, could contribute to increased tropospheric ozone and photochemical smog conditions if light levels are adequate (Crutzen and Birks, 1982, Izrael et al., 1984; Izrael, 1984). Penner (1983) and Pittock et al. (1986), however, suggest that the smoke would not allow significant build-up of the gases which could contribute to ozone formation. There is also the possibility of emissions of nitrogen and sulfur oxides in the fire plumes that could lead to gas-to-particle conversion and to localized acid deposition. The smoke-induced changes in the meteorology could aggravate some aspects of these pollution problems in localized areas by reducing vertical mixing and dispersion, particularly by the creation of an intense near surface inversion that could trap emissions from the long-lasting smoldering phase of the fires. Reduction in precipitation could also reduce the rate of acid deposition, although the rain and the fog that could be formed may be highly acidic.

It has also been suggested that direct emissions from the fires (carbon dioxide, methane, etc.) and induced changes in atmospheric composition (tropospheric ozone, upper tropospheric and stratospheric water vapor) could induce a slight warming due to an increase in the strength of the greenhouse effect. Generally, these effects would be small compared to smoke effects (see NRC, 1985; Golitsyn and Phillips, 1986).

6.3 Radionuclides

The SCOPE-ENUWAR study (Pittock et al., 1986) updated the NAS (1975) estimates of the potential radionuclide dose from a nuclear war. The new estimates suggest that 5–10% of northern hemisphere land areas could receive acute, short-term potentially lethal doses from local fallout as a result of the baseline nuclear war scenario, assuming that no protective measures are taken. As discussed in some recent comments on these results (e.g., Turco, 1986; Knox and Shapiro, 1986), the estimated extent of these contaminated areas is strongly dependent on the scenario (number and location of surface bursts) and other assumptions.

The northern hemisphere mid-latitude average global long-term fallout dose (defined as the 50-year integrated external gamma ray dose assuming no protection or weathering) is estimated to be on the order of 20–50 rads (Knox, 1983b; Turco et al., 1983; Pittock et al., 1986). This estimate can be contrasted to the NAS (1975) estimate of about 10% of this amount, which resulted mainly from their use of a scenario with many high yield weapons. Levels greater than 50 rads would occur in areas where the early plume was scavenged by precipitation. These doses would be reduced somewhat (perhaps 10–20%) by the stabilization of the troposphere and reduction in precipitation over land caused by the smoke injection (Pittock et al., 1986). The long-term dose could be substantially increased if concentrated attacks on the world's nuclear power facilities were to loft the long-lasting radionuclides stored or in use at these sites (Knox, 1983b; Pittock et al., 1986).

6.4 Conclusions

Many studies have considered solely the effects of injection of carbonaceous smoke into the atmosphere. A major nuclear exchange, however, would also cause the injection of a variety of other radiatively or chemically active substances. For example, the sub-micron dust particles lofted into the stratosphere by high-yield surface bursts could cause effects equivalent to that of a very large volcanic eruption, i.e., a mean surface cooling of the order of 1°C or more lasting a year or longer. On the other hand, the injection of a large amount of dust may also inhibit subsequent smoke ascent into the upper troposphere and stratosphere and moderate transport of smoke into the southern hemisphere. Further, nitrogen oxides produced at the high temperatures of the shock waves and fireballs could deplete stratospheric ozone significantly. Smoke-induced circulation changes could further reduce stratospheric ozone. The coupled chemical-climatic simulations needed to assess such effects have not yet been possible. Short-term local radioactive fallout could produce potentially lethal levels of radiation dose over approximately 5 to 10% of the land areas of the major nuclear alliances. Long-term global fallout could produce doses of 20 to 50 rads (50 year external gamma dose) in northern hemisphere mid-latitudes. Local and global fallout levels are, however, highly sensitive to the nuclear war scenario.

7. CONCLUDING REMARKS

During the last several years, comprehensive three-dimensional atmospheric circulation models, including detailed parametric formulations of a wide range of climatologically significant processes, have been applied to study the potential consequences of a major nuclear war involving the injection of smoke which could result from the large-scale fires ignited by such an exchange. For plausible smoke injections during the warm season of the year, all model calculations suggest that a significant climatic perturbation would result. In the lower range of smoke injection scenarios (producing of order 10 Tg of highly carbonaceous smoke), smoke would act primarily to inhibit convection and rainfall, especially over land areas, including possibly some disruption of the summer monsoon. The upper range of smoke scenarios (of order 100 Tg of highly carbonaceous smoke) would cause not only rapid and sharp decreases in land temperature and precipitation (a mid-latitude average land-temperature drop of the order of 20°C, up to perhaps twice this amount in continental interiors), but also seems likely to leave enough smoke in the atmosphere to persist into the following warm season, inducing a cooling of several degrees. Although many uncertainties must be reduced to provide more quantitative relationships between smoke characteristics and climatic effects, the important conclusion of the previous report (Golitsyn and Phillips, 1986) continues to be valid:

> The prediction of serious temperature changes in the weeks following *the creation of 10^{14} to $2 * 10^{14}$ grams of* nuclear *smoke* [equivalent to current estimates of an average hemispheric absorption optical depth of the order of unity] 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.

These studies have been made possible by the development of realistic climate models. In the face of the many remaining oversimplifications and deficiencies, the on-going WCRP activities aiming to refine the climate models will help to narrow the uncertainties while an even wider field of atmospheric physics and chemistry needs to be investigated to arrive at more encompassing assessments of the environmental impacts of a major nuclear war.

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REFERENCES

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, 24–30 (in Russian).

Aleksandrov, V.V. and Stenchikov, G.L., 1983: On the modelling of climatic consequences of nuclear war. Proc. Appl. Math., Comp. Centre, USSR Ac. Sci.

Aleksandrov, V.V. and Stenchikov, G.L., 1984: Numerical simulation of the climatic consequences of a nuclear war. USSR Comp. Math. and Math. Physics, 24, 140–144 (in Russian). English translation 24, 87–90.

Andronova, A.V., Anikin, P.P. et al., 1986: Investigation of aerosol formation upon combustion of various materials and their optical properties. In: Combustion of heterogeneous and gaseous systems. Materials of VIII All-Union Symposium on Combustion and Explosion. Chemical Physics Institute of USSR Ac. Sci., 124–127.

Bacon, D.P. and Sarma, R.A., 1987: Smoke injection into the atmosphere from large area fires. Submitted to J. Climate and Applied Meteorology.

Berry, M.V. and Percival, I.C., 1986: Optics of fractal clusters such as smoke. Optica Acta, 33, 577–591.

Bing, G., 1985: Estimates of total combustible material in NATO and Warsaw Pact countries. LLNL Report UCRL-93192, Livermore, California.

Birks, J., 1987: Atmospheric chemistry following a nuclear war. DNA Global Effects Program Technical Meeting, April 7–9, 1987, Santa Barbara, California.

Bradley, M.M., 1986: Numerical simulation of nucleation scavenging within smoke plumes above large fires. Lawrence Livermore National Laboratory report UCRL-95036, Livermore, California.

Bradley, M.M., 1987: Nucleation scavenging of smoke aerosol above intense fires: Three-dimensional simulations. IUGG-IAMP General Assembly, 9–22 August 1987, Vancouver, Canada.

Brinkman, A.W. and J. McGregor, 1983: Solar radiation in dense Saharan aerosol in Northern Nigeria. Q. J. Roy. Met. Soc., 109, 831–897.

Bruce, C.W. and Richardson, N.M., 1983: Propagation at 10μm through smoke produced by atmospheric combustion of diesel fuel. Applied Optics 22, 1051–1055.

Budyko, M.I., Golitsyn, G.S. and Izrael, Yu.A., 1986: Global climatic catastrophies. Hydromet. Publ. House, Leningrad, 160 p.

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

Cess, R.D., Potter, G.L., Ghan, S.J. and Gates, W.L., 1985: The climatic effects of large injections of atmospheric smoke and dust: A study of climate feedback mechanisms with one- and three-dimensional climate models. J. Geophysical Research, 90, 12937-12950.

Charlson, R.J. and Ogren, J.A.. 1982: The atmospheric cycle of elemental carbon. 3-18 in Particulate Carbon: Atmospheric Life Cycle, G.T. Wolff and R.L. Klimisch (eds.), Plenum, New York.

Clarke, A.G. and Papanayotou, Y., 1986: The influence of coagulation on the optical properties of smoke. SCOPE-ENUWAR Paper FW.09.86.

Cotton, W.R., 1985: Atmospheric convection and nuclear winter. Amer. Scientist, 73, 275-280.

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

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

Crutzen, P.J. and Birks, J.W., 1982: The atmosphere after a nuclear war: Twilight at noon. Ambio, 11, 114-115.

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

deHaas, N., Fristrom, R.M., Linevsky, M.J. and Silver, D.M., 1986: Smoke scavenging by atmospheric ozone as a possible factor in the nuclear winter problem. Johns Hopkins APL Technical Digest 7, No. 2.

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

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

Gershenzon et al., 1987. Journal of Physical Chemistry (in Russian), January.

Ghan, S.J., MacCracken, M.C. and Walton, J.J., 1985: Climatic response to large summertime injections of smoke into the atmosphere: Changes in precipitation and the Hadley circulation. Lawrence Livermore National Laboratory Report UCRL-92324. Presented at IAMAP, Honolulu.

Ghan, S.L., MacCracken, M.C. and Walton, J.J., 1987a: The climatic response to large atmospheric smoke injections: Sensitivity studies with a tropospheric general circulation model. J. Geophys. Res. (submitted).

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

Ginsburg, A.S. and Golitsyn, G.S., 1986: Comparative analysis of mass forest and nuclear fires. Paper presented at the Second All-Union Conference of Scientists for Peace and Nuclear War Prevention, Moscow, 27–29, May 1986.

Golding, B.W., Goldsmith, P., Machin, N.A. and Slingo, A., 1986: Importance of local mesoscale factors in any assessment of nuclear winter. Nature, 319, 301–303.

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

Golitsyn, G.S., 1986b: Nuclear winter: New developments from USSR. Environment, 28, No. 8, pp. 5,44.

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

Golitsyn, G.S. and Shukurov, A.Kh., 1987. Temperature effects of dust aerosols on the example of dust storms in Tadjikistan. Proc. USSR Acad. Sci.

Gostintsev, Yu.A. et al., 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.

Harwell, M.A. and Hutchinson, T.C., 1986: Environmental Consequences of Nuclear War. Vol II., Ecological and Agricultural Effects. SCOPE 28, Wiley, 458p.

Izrael, Yu.A., 1984: Ecology and control of the state of environment. Leningrad, Hydromet. Publishing House, 560 p.

Izrael, Yu.A. and Karol, I.L. et al., 1984: Modelling changes of atmospheric composition and thermal regime after possible nuclear war. Paper presented at USSR-USA meeting on atmospheric trace gases, Vilnius.

Izrael, Yu.A. and Karol, I.L., 1985: Modelling the global influence of nuclear war on the ozonosphere. Abstracts of papers at All-Union Symposium on Atmospheric Ozone. Leningrad, Main Geophys. Observatory, p. 38–39.

Joint Scientific Committee (JSC), 1985. Report of the Sixth Session of the Joint Scientific Committee, World Meteorological Organization report WMO/TD-No. 54, Geneva.

Knox, J.B., 1983a: Precipitation scavenging: Effects on deposition of radioactivity and smoke. EOS, 64, 659.

Knox, J.B., 1983b: Global scale deposition of radioactivity from a large scale exchange. 29–46 in Proceedings of International Seminar on Nuclear War, Erice.

Knox, J. and Shapiro, C., 1986: The real hazards of nuclear fallout. Nature, 321, 21–22.

Kondratyev, K.Ya., Vasilyev, O.B. and Grishechkin, V.S., 1971: Concerning the spectral distribution of the radiative flux of heat into the atmosphere. Doklady Acadi. Sci. USSR, 198 (S), 322–327.

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

Ledley, T.S. and Thompson, S.L., 1986: Potential effects of nuclear war smokefall on sea ice. Climatic Change, 9 155–171.

Lin, Yuh-Lang, Farley, R.D., and Orville, H.D., 1983: Bulk parameterization of the snow field in a cloud model. J. Climate and Applied Meteorology. 22, pp. 1065–1092.

MacCracken, M.C., 1983: Nuclear war: Preliminary estimates of the climatic effects of a nuclear exchange. 161–183 in Proceedings of International Seminar on Nuclear War, Erice.

Mahrer, Y. and Pielke, R.A., 1977: A numerical story of the airflow over irregular terrain. Beitr. z. Physik d. Atmos., 50, 98–113.

Malone, R., 1987: A comparison of Eulerian and Lagrangian methods for tracer transport in a GCM. DNA Global Effects Program Technical Meeting, April 7–9, 1987, Santa Barbara, California.

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

Mettlach, T.R., Haney, R.L., Garwood, R.W. and Ghan, S.J., 1987: The response of the upper ocean to a large summertime injection of smoke in the atmosphere. Journal of Geophysical Research 92, No. C2, pp. 1967–1974.

Mitchell, J.F.B., 1987: A "nuclear winter" sensitivity study. SCOPE-ENUWAR paper BA.30.87.

Molenkamp, C.R., 1986: Simulation of coastal flow fields when the incident solar radiation is obscured. Lawrence Livermore National Laboratory report UCRL-94934, Livermore, California.

Mulholland, G., 1986: Smoke emission. Report on DNA/NBS Workshop on Smoke Emission and Properties, November 13–14, 1986, Gaithersburg, Maryland.

National Academy of Sciences (NAS), 1975: Long-Term Worldwide Effects of Multiple Nuclear Weapons Detonations. Washington, D.C., National Academy Press.

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

Oboukhov, A.M. and Golitsyn, G.S., 1983: Possible atmospheric consequences of nuclear conflict. Zemlya i Vselennaya (Earth and Universe), No. 6, 5–13 (in Russian).

Patterson, E.M., McMahon, C.K. and Ward, D.E., 1986: Absorption properties and graphitic carbon emission factors of forest fire aerosols. Geophys. Res. Letters, 13, 129–132.

Penner, J.E., 1983: Tropospheric response to a nuclear exchange. 94–106 in Proceedings of the International Seminar on Nuclear War, Erice.

Penner, J.E., 1986a: Uncertainties in the smoke source term for nuclear winter studies. Nature, 324, 222–226.

Penner, J.E., 1986b: The effect of aging on smoke optical properties and scavenging characteristics. UCRL-95645, November 1936 (also SCOPE-ENUWAR Paper BA.10.87).

Penner, J.E. and Edwards, L.L , 1986: Nucleation scavenging of smoke and aerosol particles in convective updrafts. Preprint Volume of 23rd Conference on Radar Meteorology and the Conference on Cloud Physics, Snowmass, Colorado.

Penner, J.E. and Porch, W.M., 1987: Coagulation in smoke plumes after a nuclear war. Atmos. Environment, 21, 957–968.

Pittock, A.B., Ackerman, T.P., Crutzen, P.J., MacCracken, M.C., Shapiro, C.S. and Turco, R.P., 1986: Environmental Consequences of Nuclear War. Vol. I, Physical and Atmospheric Effects, SCOPE 28, Wiley, 360 p.

Pittock, A.B., Frederiksen, J., Garratt, J.R. and Walsh, K., 1987: Climatic effects of smoke and dust produced from nuclear conflagrations. IUGG-IAMP General Assembly, 9–22 August 1987, Vancouver, Canada.

Pittock, A.B. and Garratt, J.R., 1987: Sensitivity studies on nuclear winter effects in the southern hemisphere with water implications. SCOPE-ENUWAR paper BA 25.87.

Porch, W.M., Penner, J.E. and Gillette, D.A., 1986: Parametric study of wind generated super-μm particle effects in large fires. Atmos. Environ., 20, 919–929. See also comments, in press, 1987.

Reitter, T.A., 1986. Additional results of the simulation of large-scale urban fires using the LUF code. Lawrence Livermore National Laboratory report UCID-20910, Livermore, California.

Robock, A., 1984: Snow and ice feedbacks prolong effects of nuclear winter. Nature, 310, 667–670.

Robock, A., 1987: Surface temperature effects of smoke plumes. DNA Global Effects Program Technical Meeting, April 7–9, 1987, Santa Barbara, California.

Roessler, D.M. and Faxvog, F.R., 1980: Optical properties of agglomerated acetylene smoke particles at 0.5145-μm and 10.6-μm wavelengths. J. Opt. Soc. Am., 70, No. 2, pp. 230–235.

Slingo, A. and Goldsmith, P., 1985: Nuclear winter: Calculations of short wave radiative effects of soot aerosols. Dyn. Climatol. Tech. Note 24, Met. Office, Bracknell, UK.

Small, R.D., 1987. Smoke produced by a nuclear attack on the United States. DNA Global Effects Program Technical Meeting, April 7–9, 1987, Santa Barbara, California.

Small, R.D., Blair, J.M. and Heikes, K.E., 1987: Clouds formed by large area fires. Third International Symposium on Density Stratified Flows, February 1987, Pasadena, California.

Small, R.D. and Bush, B.H., 1985: Smoke production from nuclear explosions in non-urban areas. Science, 229, 465–469.

Sokolik, I.N., Tarasova, T.A. and Feigelson, E.M., 1986: Optical characteristics of the smoky atmosphere and radiative heating. Meteorologia i Hydrologia, No. 11, 31–26 (in Russian).

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, Nanka, 66–99 (in Russian).

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

Thompson, S.L., Ramaswamy, V. and Covey, C., 1987: Atmospheric effects of nuclear war aerosols in GCM simulations: Modelling of smoke microphysical processes. J. Geophys. Res. in press.

Tripoli, G.J., 1986: Convective and mesoscale responses to firestorms, DNA Global Effects Program Technical Meeting, February 25–27, 1986, Moffet Field, California.

Tripoli, G.J., 1987: Personal communication. DNA Global Effects Program Technical Meeting, April 7–9, 1987, Santa Barbara, California.

Tripoli, G.J. and Kang S.-W. 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., 1986: Radioactive fallout revisited. Letter to Nature (submitted).

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

Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J. and Sagan, C., 1987: Climate and smoke: An appraisal of nuclear winter, SCOPE-ENUWAR Paper.

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

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, 20, No. 4, 665–680.

WCP-55: Experts meeting on aerosols and their climatic effects. WMO, Geneva, December 1983.

Williamson, R.B., Dud, R., Mowrer, F.W., Brown, N.J. and Novakov, T., 1986. Smoke emission factors from burning wood and asphalt as measured in medium scale experiments. Berkeley Fire Research Laboratory preprint, U.C. Berkeley, Berkeley, California.

Xu Guo-chang, Ghen Min-lian, Wu Guo-Xiant, 1979: On an extraordinarily heavy sandstorm on April 22nd in Gansu. Acta Meteorologica Sinica, 37, No. 4, 26–35.

Zak, B., 1987: Plume characterization studies of hydrocarbon pool fires. DNA Global Effects Program Meeting, 7–9 April 1987, Santa Barbara, California.

Zvenigorodsky, S.G. and Smyshlyayev, S.P., 1985: On possible ozone content changes for intense perturbation of aerosol components. Izvestia-Atmospheric and Oceanic Physics, 21, No. 10, 1056–1063.