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THE ENVIRONMENTAL EFFECTS OF NUCLEAR WAR

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ABSTRACT

Substantial environmental disruption will significantly add to the disastrous consequences caused by the direct thermal, blast, and radiological effects brought on by a major nuclear war. Local fallout could cover several per cent of the Northern Hemisphere with potentially lethal doses. Smoke from post-nuclear fires could darken the skies and induce temperature decreases of tens of degrees in continental interiors. Stratospheric ozone could be significantly reduced due to nitric oxide injections and smoke-induced circulation changes. The environmental effects spread the consequences of a nuclear war to the world population, adding to the potentially large disruptive effects a further reason to avoid such a catastrophe.

INTRODUCTION

> "The scientific evidence is now conclusive that a major nuclear war would entail the high risk of a global environmental disruption. The sensitivity of agricultural systems and natural ecosystems to variations in temperature, precipitation and light leads to the conclusion that the widespread impact of a nuclear exchange on climate would constitute a severe threat to world food production. The socio-economic consequences in a world intimately interconnected economically, socially and environmentally would be grave."[1] United Nations, Report of the Secretary General, 1988.

Starting with the explosions over Hiroshima and Nagasaki in 1945, the prospect of the extensive destructive effects of a nuclear war have served as a primary deterrent to conflict among the major powers. Given present arsenals, even a nuclear attack focused on the opponent's nuclear and command forces would likely involve the deaths of tens of millions of people. A major countervalue exchange, the underlying premise of mutual assured destruction, would lead to deaths and injuries of a few hundred million and extensive blast and fire damage to numerous urban areas.[2] While active and functional civil defense actions might reduce deaths several fold, the destruction done to medical, water, electric, sewage, distribution, economic, and food supply networks would pose such serious problems to surviving populations that millions more would likely die during the following few months. This aspect of nuclear war impacts on the combatants seems too often to be understated.

While recognition of such disastrous consequences from the direct effects alone (i.e., the fire, blast, radiological and, less importantly, electromagnetic pulse) has and continues to be the primary basis for deterrence between the potential combatant nations, it has been the consequent global-scale environmental effects that have created the most concern among non-combatant nations. Although such environmental consequences would also affect the combatant nations, they are generally viewed as a secondary concern. Conversely, until recently[3] non-combatant nations have generally ignored the severely disruptive consequences of the destruction of economic and commercial networks, especially in our increasingly interdependent world.

To provide insight into the potential deterrent effects among non-combatants of the threat of the consequences, as well as to better understand the basis of the resulting stimulation of such nations to support arms control initiatives, it is useful to review the environmental consequences of nuclear war, particularly those extending to the global scale. These environmental effects arise from the various gaseous and particulate injections into the atmosphere (see Figure 1), where they can be dispersed over long distances. (The effects of liquid and particulate releases into water bodies and onto the land surface, including the deposited early fallout of radionuclides, are generally localized, and will not be covered in this review.) Emissions to the atmosphere will be divided based on their effects:

1. Radionuclides that cause human exposure;
2. Smoke and dust that alter climate;
3. Nitrogen oxides and other species that alter atmospheric chemistry.

The injections and consequences of each of the major emissions will be covered in successive sections. In this review of potential effects, the arbitrary assumption will be made that the nuclear war involves explosion of about 10,000 strategic nuclear weapons totalling about 5000 Mt. Such an exchange is within plausible reach given the existent arsenals and it thus is perceived as a possible exchange by non-combatant nations. The extent to which the potential environmental consequences are dependent on this assumption will be discussed further below, but it appears that (within the limits imposed by present arsenals) there is greater sensitivity of potential environmental effects to target characteristics and the assumptions concerning how weapons are allocated to and exploded over targets than to the actual number and size of weapons.

Finally, this review attempts to focus more on concepts, providing order of magnitude estimates of emissions and atmospheric consequences, calibrated based on more detailed reviews carried out by SCOPE,[3,4] Golitsyn and MacCracken,[5] and others. This is done to minimize questions arising from use of theoretical models in such calculations—the potential effects are sufficiently robust that key assumptions, critical unknowns, and the potential global-scale significance of the emissions can be illustrated schematically. Resolving the

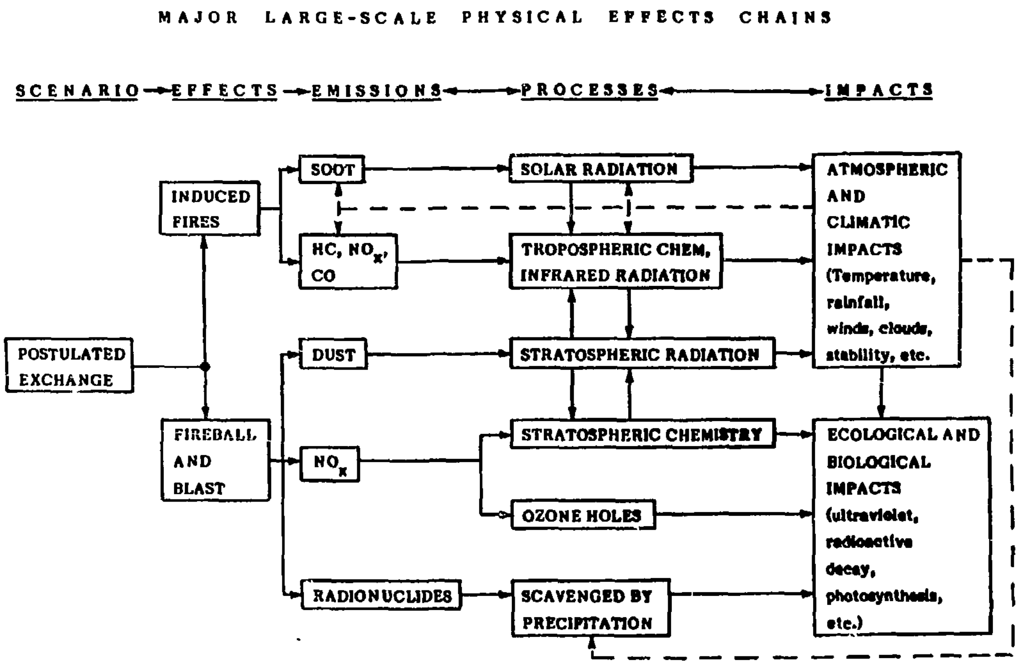

Figure 1: Effects chains for the major species emissions resulting from a nuclear war.

uncertainties and providing spatial and temporal details certainly requires theoretical approaches and models, but the most important insights are readily apparent.

RADIONUCLIDES

While the blast and heat radiation (flash) are the primary destructive agents of a nuclear explosion, the creation and dispersal of radioactive debris has the potential of extending the impacts both in space and in time. Estimation of the effects of the radionuclides depends on many factors, including the type and yield of the weapons, the details of the explosion (e.g., height, surface type, etc.), the meteorology, and a range of other factors.

Weapon type determines the amount of radioactive loading of the debris that is created. The fission component of a nuclear weapon explosion transforms uranium or plutonium into a complex mix of more than 300 lighter isotopes that have a wide range of decay times and emit primarily beta particles and gamma radiation: about 10% of the energy of a fission weapon ends up in the radioactive debris products that persist for more than a minute after the explosion.*[6] Some uranium or plutonium may also be left, but is only harmful if inhaled because it gives off alpha particles as a decay product. The fusion component of the explosion transforms light nuclei into an array of heavier isotopes, including tritium, but does not contribute significantly to the overall inventory of fission products. Carbon-14 is produced by neutron activation of atmospheric nitrogen. Fusion weapons are generally driven by a fission trigger. Estimates of the radioactive effects of a nuclear war typically approximate the fission product yield as half of the total yield (i.e., the fission fraction is typically assumed to be one-half; other choices may be scaled appropriately). For each kiloton of fission energy yield, approximately 3×10^{23} fission product atoms are generated, weighing almost 60g and at 1 minute generating of order 10^{21} disintegrations per second.[6] For reference in later estimating local fallout effects, observations indicate that if the radioactivity from a nuclear explosion were deposited evenly over a smooth infinite plane such that the products from each 1 kiloton of fission energy yield covered a square mile, the dose rate (in tissue) at a height of 3 feet above the plane would be approximately 2900 rads per hour at 1 hour after the explosion.[6] Starting with the fission debris present at one hour, the dose rate is reduced by approximately a factor of ten for every factor of seven in time (over the first six months). This is quite close to a $t^{-1.2}$ time dependence.

Several factors combine to determine how and where the radioactive debris is actually deposited and how rapidly this occurs, which in turn determines the extent of decay that has occurred prior to deposition (thereby reducing any subsequent time-integrated dose). In addition, the ground is not flat, deposition is not uniform, people are usually mobile and protected (by clothes, as well as by structures), and people and the fallout may not be collocated. As a

* This energy, since not part of the explosive yield, is not included in stating the yield.

result, estimating impacts can be highly dependent on assumptions and special conditions. The analysis here will discuss only important controlling factors; for a more thorough analysis, see Pittock et al.[4] and Institute of Medicine.[2]

The height of the burst (HOB) above the surface is critical in determining the size of the particles on which the radioactive debris resides, which in turn contributes to determining the rate of deposition of the particles, and the height from which the debris starts its journey towards the surface. Explosions at the surface or for which the fireball touches the surface (i.e., those for which the HOB (in feet) is less than 180 $W^{0.4}$, where W is the explosion yield in kilotons), draw large amounts of surface materials into the cloud, leading of the order of half of the hot radioactive gases to condense on relatively large particles. These relatively large particles tend to fall out of the atmosphere in the 24 hours following the explosion, creating a highly radioactive footprint often referred to as early, or local, fallout. Because it is deposited so rapidly, this fallout can contribute to the acute dose (an external gamma ray dose of approximately 450 rad received within 48 hours is often assumed lethal to 50% of a healthy population; presumably a lower dose would create similar lethality to a population simultaneously experiencing the many insults of a nuclear war).

If we assume that half of the yield of our hypothetical war is exploded at or near the surface,* that the typical yield is 500 kt, that the fission fraction is 0.5, and that half of the fission products are deposited as early or local fallout, then, using Figure 2 taken from Pittock et al.,[4] each explosion covers an area of about 350 km^2 with a minimum, unshielded dose of 450 rad within 48 hr. Assuming no overlap of fallout patterns (an assumption which, as explained in Pittock et al., is probably within a factor of a few of being correct, depending on the specific scenario), the 5000 surface burst explosions would cover an area of about 1.75 million km^2 with a 450 rad–48 hr unshielded dose, which is roughly 5% of the area of the NATO and Warsaw Pact countries. While the potential lethal area due to early fallout could be increased by a number of factors (tactical weapons effects, internal radiation, etc.), shielding and deposition of the debris over the oceans could reduce the percentage coverage. Because of the complexities of the meteorology (rainout, of the debris for example, can concentrate dosage over smaller areas) and the vagaries of the actual war scenario, significantly more accurate projections are probably not justified for the purposes of this paper. Clearly, however, local fallout would be worsened by tendencies to harden targets, thereby requiring a higher fraction of surface bursts of higher yield.

For explosions above the surface and for the half of the debris from surface bursts that ends up on small particles, the yield and HOB of the explosion determines the level of the atmosphere to which the debris cloud rises. Low-altitude (but above the surface) air bursts with yields greater than about 500 kt loft their debris into the stratosphere, where the residence time for particles in

* Surface bursts are generally viewed as preferred against hardened targets to enhance ground shock. Bursts above the surface are generally viewed as preferred against unhardened targets to maximize the area of damage.

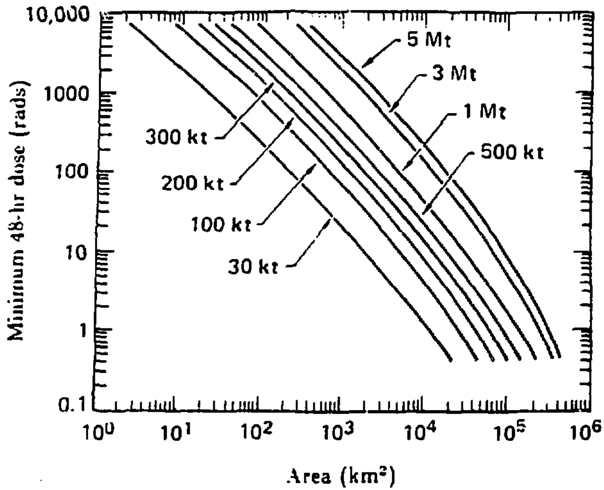

Figure 2. Fallout areas versus minimum 48-hour doses for selected yields from 30 kt to 5 Mt. The weapons were surface-burst and all-fission. These curves include an instrument shielding factor of 25%.[6] Doses within the area defined would exceed the minimum dose. (From Pittock et al.[4])

the unperturbed atmosphere is typically six months or more, a fact known from study of volcanic aerosol clouds. This part of the radioactivity spreads around the globe, mostly in the hemisphere of detonation; hence it is called global fallout. Given six months for radioactive decay, the dose rate drops by about 4 orders of magnitude.* Spreading the radioactivity from the airbursts (2500 Mt times 0.5 fission yield) and the remaining 50% from surface bursts (1250 Mt times 0.5 fission yield) over the Northern Hemisphere, depositing it all at one year and allowing for radioactive decay, gives a dose rate after one year of about 10^{-3} rad/hr, which is about one hundred times the natural background rate, and continuing to decrease. The 50-year integrated external gamma ray dose, accounting for radioactive decay and not considering protection, rough terrain, weathering, and other factors, would be of the order of a few tens of rad, which is less than the U.S. occupational safety standard of 5 rad/year. Thus, what gets into the stratosphere has relatively little practical significance, and estimates made in the 1970s, when the nuclear arsenals included many multi-megaton

* Strictly, the decay rate rule doesn't apply beyond six months.

weapons, suggested that global fallout was not a serious problem in the context of a nuclear war.[7]

Over the past decade, as the yields of nuclear weapons have decreased to average about 500 kT,[+] the importance of the radioactive debris that remains in the troposphere (roughly the lowest 10–12 km of the atmosphere, which is generally well-mixed vertically and within which precipitation systems exist) has increased. Particles in this part of the atmosphere typically have lifetimes of days to weeks, so that there is less time for both decay and for spreading. If we assume that 4000 Mt of total yield (times one half to get fission fraction) all end up in the troposphere and are deposited evenly over the approximately 10^8 km^2 between 30° and 60°N at a time of one week, the dose rate at one week is a few tenths of a rad per hour (decreased by a factor of 10 after 7 more weeks). Model calculations suggest that the total 50 year integrated dose in this latitude band (assuming no weathering or sheltering) would be of order 30–50 rad (about half during the first year), which is less than a factor of ten over the U.S. occupational standard of 5 rad/year. As shown in Figure 3, the spatial variability of this dose would be significant and could be a factor of several higher in hotspots where rainout has concentrated the radioactive deposition. Thus, although the reduction in weapons yields from megatons to hundreds of kilotons over the past decade has led to increased radionuclide doses, this intermediate fallout will likely not be life threatening in most regions, especially outside the Northern Hemisphere mid-latitudes.

These calculations have focused on external gamma ray dose. The weapons debris can also be taken up by plants and animals that are later eaten as food. Because food pathways following a nuclear war may be significantly disrupted, estimating internal dose contribution requires many uncertain assumptions. Peterson et al.[8] suggest that the internal dose due to local fallout could range from much smaller than to about equal to the external dose, depending on a wide range of factors (e.g., protection factor, diet, etc.). In general, however, it seems unlikely that the dose from contaminated food will have as severe an impact as limitations in food supply and other infrastructure problems.

In addition to radionuclides from the weapons themselves, there is the possibility that radionuclides tied up in the nuclear fuel cycle (naval reactors, power plants, reprocessing facilities, storage locations, etc.) could be released into the environment. In the vicinity of the facilities, local fallout from the assumed surface burst that would be required to overcome the containment vessel and disperse these materials,[*] would be the greater short-term problem, because the fuel cycle radionuclides involved are generally longer-lived than weapons debris; over the longer term, the fuel cycle radionuclides would contribute to a greater,

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[+] The arsenal and exchange considered here are based on Tables 2.1 and 7.7 of reference 4.

[*] There is, of course, the potential that prolonged disruption of the electrical power network may cause a failure of nuclear power plants that could also lead to radionuclide dispersal.[9]

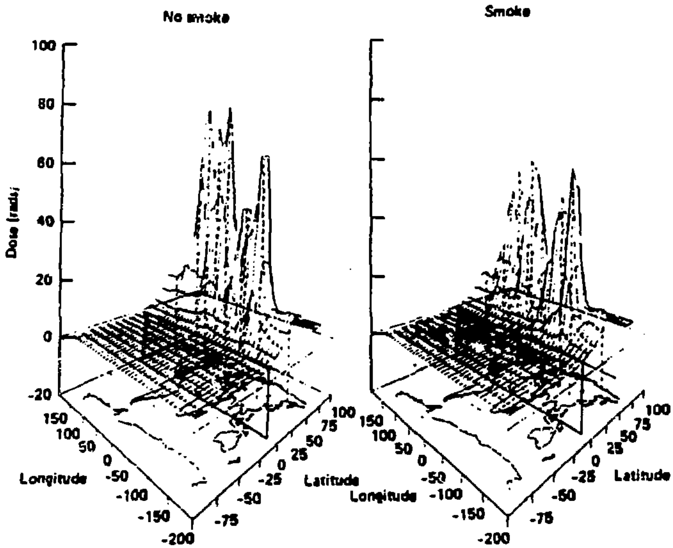

Figure 3. Comparison of radionuclide global dose distribution for cases with unperturbed and smoke-perturbed climates (tropospheric contributions only).

but prolonged, dose. For the case of intermediate and global fallout, if the nuclear explosion lofts the long-lived isotopes and mixes them with the weapons debris, rough calculations indicate that the Northern Hemisphere mid latitude 50 year external doses could be roughly tripled.[4] Quite certainly, as the Chernobyl accident demonstrated, rather large areas could have levels where, given peacetime standards, habitation would need to be prohibited. In that these areas could be far from the target area, it would seem prudent for nations to avoid direct targeting of nuclear facilities with thermonuclear weapons.

CLIMATIC PERTURBATIONS

Nuclear explosions lead to the injection of a range of substances into the atmosphere that could perturb the atmosphere, leading initially to modest changes in atmospheric conditions about the present averages (i.e., to perturbing the "weather") and, in addition, were emissions massive enough, to changes in the average state of the atmosphere over weeks, months, and even years (i.e., to perturbing the "climate"). Nitric oxide created by the nuclear fireball reacts with ozone to become nitrogen dioxide, an absorber of solar radiation. Surface materials. usually referred to as dust, are carried upward from surface and near-surface bursts by the mushroom cloud where they act like volcanic aerosol injections to whiten the sky by increasing the scattering of solar radiation. Smoke, especially black smoke created predominantly in urban fires started by nuclear explosions, is carried upward in the heat-driven fire plumes to levels where its absorption of solar radiation takes place at altitudes above most of the "greenhouse" gases that trap infrared radiation and add warmth to the planet.

The effects of nitrogen dioxide and dust injections alone on the atmosphere seem likely to involve perturbations that are not unlike the anomalous summer or winter weather experienced in the absence of nuclear explosions. That this might be the case can be seen by comparing the radiative effects of a nuclear dust loading with those caused by a major volcanic injection of sulfate-creating gases. Although the actual value would depend on specific soil conditions and other factors, observations suggest that a typical surface burst would lead to lofting of about 0.3 Tg/Mt of dust into the stabilized cloud ($1\ Tg = 10^{12}g = 10^6$ metric tons). About 8% of this mass, or about 0.025 Tg/Mt, has a radius of less than one micrometer.[10] The dust with radius larger than 1 μm generally has a fall velocity such that it would be deposited within days to weeks, insufficient time to induce a significant disturbance to the atmospheric circulation, although like the Mt. St. Helens dust injection, local daily maximum temperatures under the dust cloud would be reduced during this period. If we assume that the 2500 Mt of surface burst explosions used above loft all of the submicron dust into the stratosphere, and then spread the dust over the Northern Hemisphere, there would be about 0.25 g/m^2 [4,11] (with more careful analyses, one would get about half of the injection calculated here). Dust acts mainly to scatter solar radiation, with an extinction optical extinction efficiency of about 2 m^2/g; when multiplied by the dust column, this gives an optical depth of about 0.5, meaning that for an average solar zenith angle of 60°, e^{-1} of the direct solar radiation would be transmitted. Were dust a perfect absorber, the absorption of this radiation in the stratosphere above the greenhouse gases could lead to substantial surface cooling (as is the case for smoke). But dust scatters of order 90% of intercepted radiation forward (downward), creating a whitening of the sky as do water clouds (which have optical depths up to ten or more). In terms of potential atmospheric effects, the optical depth of 0.5 from nuclear-injected dust can be compared to a hemispheric average optical depth of about 0.15 following the El Chichon volcanic eruption. Although unusual weather induced by an El Niño event followed, the connection is, at best, tenuous and there was virtually no effect on global average temperature. Larger eruptions, for example Krakatoa in 1883 and the much larger Tambora in 1815, also seem to have preceded unusual weather events (even unseasonal frosts), but without substantial or lasting perturbations to the underlying climate.

Because smoke particles are much darker than dust, the potential effects on the atmosphere of smoke injections are much more severe, as Crutzen and Birks,[12] Turco et al.,[10] NRC,[11] and Pittock et al.[4] all describe. These studies draw on a wide array of laboratory, field, theoretical, and numerical experiments and analyses in an attempt to improve understanding of an event filled with uncertainties and unknowns; this is one large event for which, drawing from Heisenberg, conducting the full experiment as a means of reducing uncertainties would destroy the object of the experiment. Although we can not, therefore, foresee the details, or perhaps even major aspects, the potential for large climatic effects is readily illustrated.

To estimate the potential effects, we need to estimate the amount of smoke injected and its climatic effect. If we assume 2000 500 kt nuclear explosions (or equivalent) occur over urban/suburban areas, a scenario plausible either as a direct result of declared retaliatory policy (i.e., MAD) or as a side-effect of an allout attack on military and industrial targets, the area exposed to ignition would be of order 100,000 km^2, even allowing a factor of 3 reduction to account for the limited size of such areas, open areas, and for overlap of nearby explosions. Assuming a combustible fuel loading of 30 kg/m^2 (i.e., combustion of 3000 Tg of material, which is of order 25–40% of total combustible fuel in NATO and Warsaw Pact countries[13]) and a soot emission factor of 2% (which allows for a mix of wood and petroleum-based materials such as plastics, etc. and ignores the additional smoke mass made up of scattering constituents), submicron soot emissions total 60 Tg. A major uncertainty concerns the fraction of these emissions that might be scavenged as a result of rain induced by the very rapidly rising fire plume, an effect that apparently led, for example, to the "black rain" following the Hiroshima explosion. Field experiments using forest fires and oil pool fires are being used to investigate this phenomenon. The NRC[11] report suggested that the uncertainty spanned the range 10 to 90%; uncertainties are due mainly to limited understanding and treatment of microphysical processes, including nucleation, capture, electrical processes and more. For the present exercise, assume that half of the soot will survive early time removal without being agglomerated into supermicron, easily scavenged particles.

The hot fires, behaving much like large thunderstorm clouds, would thus loft 30 Tg of sooty material into the upper troposphere (5–10 km above the surface), with some possibly reaching even into the lower stratosphere. Such soot has a specific absorption coefficient of order 10 m^2/g, leading to an absorption optical depth of about 1.2 when spread over the entire Northern Hemisphere. Penner[13] considers the uncertainties in the various factors contributing to this number and suggests a range of from about 0.1 to about 5 (her estimates assume spread over half of the Northern Hemisphere).

With no analog to such an event (except perhaps following impact of an asteroid or comet), numerical models are typically used to estimate the potential impact. Clearly, however, it will be large. Assuming an average solar zenith angle of 60°, only about 10% of the solar radiation will make it through the smoke cloud. (Spreading of the aerosol evenly over a large area and not allowing scavenging maximizes the absorption, however, so the actual effect will be less.) This factor of 10 effect can be compared to the change of about a factor of 2 decrease in hemispheric average solar absorption from summer to winter. It is not surprising, therefore, that the phrase "nuclear winter" has been adopted to describe the effect.

The importance of the altitude and high absorption coefficient of the smoke can be illustrated analytically using a highly simplified representation. Consider a model atmosphere consisting of two layers, with solar and infrared radiative fluxes represented at the top of the upper layer, between the upper and lower layers, and between the lower layer and the surface (assumed to be non-reflecting). Then, assuming radiative equilibrium of each system component (which won't actually occur due to the high thermal capacity of the ocean), the infrared radiative flux from the surface is

$$\sigma T_s^4 = S_o(1 - r_u)(1 - r_l)G$$

where

σ = Stefan-Boltzman constant
T_s = surface temperature
S_o = solar insolation at the top of the atmosphere
r_u, r_l = reflectivities of the upper and lower layers, respectively, and
G = greenhouse factor.

The Greenhouse factor is dependent on the absorptivities, a, of visible light passing through the two layers, and the infrared emissivities, e, of the two layers, such that

$$G = \frac{4 - e_u e_l - a_u[2 - e_l(1 - e_u)] - a_l(2 - e_u)(1 - a_u) + \frac{r_l}{(1-r_l)} a_u(2 - a_u)(2 - e_l)}{(2 - e_u)(2 - e_l)}$$

where multiple reflections between cloud layers have been ignored.

Plausible parameters for the present atmosphere, assuming each layer is made up of clouds and various greenhouse gases, are:

S_o = 340 W/m^2
r_u = 0.09 (30% high cloud cover, 30% reflectivity)
a_u = 0.05
e_u = 0.3
r_l = 0.24 (40% low cloud cover, 60% reflectivity)
a_l = 0.15
e_l = 0.8

These parameters give $G = 1.68$ and $T_s = 289$ K and a planetary radiating temperature of 255 K; were there no atmospheric layers and the planet completely absorbing, $G = 1.0$ and $T_s = 277$ K, illustrating the importance of greenhouse gases in warming the Earth.

If the top layer becomes totally soot-filled such that $r_u = 0$ and $a_u = 1$, which would be the extreme case for smoke injections, then T_s drops to 244 K, even colder than the planetary radiating temperature. This can occur because the only energy now available to the layers below is the infrared energy radiated downward by the top layer (which is, in this approximation, half the solar energy plus half of the absorbed infrared energy coming up from below). The surface temperature would drop even lower if the upper layer also maintains some reflectivity. Such a result was found by Turco et al.[10] who used a one-dimensional radiative-convective model to simulate a land covered planet.

Several variants provide interesting insights. Were the smoke to spread only throughout the lower atmosphere (such that $a_l = 1$ and $r_l = 0$), then T_s would decrease to only 275 K, a consequence of much of the sunlight being absorbed at altitudes below the greenhouse gases; thus, the higher the smoke is injected, the larger the temperature reduction. Were the smoke highly absorbing in the infrared such that the emissivity approached unity (which is not likely to be the case because the smoke particles tend to be submicron in size), the surface temperature reductions would be to 278 K and 286 K for soot in the upper and lower layers, respectively; thus, the low IR opacity of the smoke also exacerbates the cooling.

These calculations are for equilibrium conditions, which implies that the surface in effect has zero heat capacity during the time that the smoke is present. Because of the large ocean heat capacity, this is not the case; ocean surface temperatures would cool only very slowly as the oceans gave up their heat to warm the atmosphere, helping to buffer the cooling tendency over land. That this buffering will be substantial is evident by applying the formula for a volcanic dust injection which might increase r_u to 0.12. Such an increase, by the formula, would lead to a global average temperature reduction of about 2.4 K, whereas past volcanic aerosol injections with such a reflectivity appear to induce coolings of about one-third this amount.

When more sophisticated climate models are applied to the problem of smoke injections,[14,15,16] they all find that surface temperatures, particularly over continental interiors, are quite sensitive to smoke injections. This is especially true in summer when solar radiation is the primary determinant of surface temperature, but less so in winter when continental temperatures are maintained to a large extent by heat transport from the ocean to the atmosphere and then over land. The model calculations indicate that massive smoke injections can reduce summertime surface temperatures by 10–20 K, with episodes to near or below freezing, in the weeks following the war (see Figure 4).

Two important factors have also been identified that enhance the persistence of the perturbation, particularly in the summer. Cooling of the lower troposphere and warming of the upper troposphere by solar heating of the smoke lead to increased atmospheric stability, which suppresses the convective precipitation that would normally cleanse the smoke particles from the atmosphere. The heating also promotes lofting of the smoke to higher altitudes, even well up into the stratosphere, where it can spread globally. Once at these altitudes, the smoke lifetime increases from weeks to a year or more, introducing the potential for the smoke to induce a long-term temperature perturbation of several degrees, which would make agriculture more difficult during the recovery phase—not just in the combatant nations, but around the world.

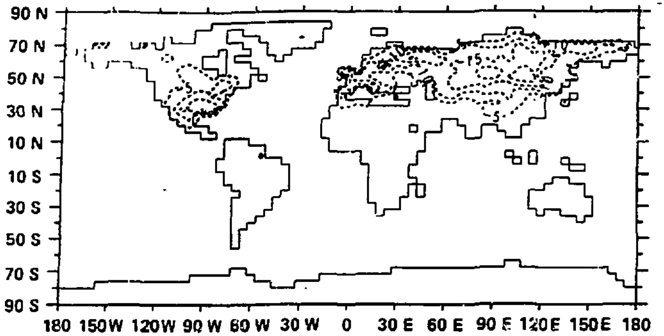

Figure 4. Distribution of surface air temperature change (smoke − control) averaged from day 1–10 following the nominal injection. Contour levels are −20, −15, −10, −5 K, with negative isotherms dashed. (From Ghan et al.[16])

The recognition of this potential for both acute and chronic climatic perturbations has led to several inquiries into the likely impacts of such changes on societal activity. Harwell and Hutchinson,[3] concurred in by a special United Nations panel,[1] suggest that such climatic effects and the societal disruption of a major nuclear war pose the threat of starvation to a majority of the world's population, making the potential for deaths from smoke effects up to several times larger than from the direct fire, blast, and radiclogical consequences.

ATMOSPHERIC CHEMISTRY

Nuclear explosions lead to the injection of many different gases into the atmosphere. Gases that affect the climate and chemistry of the global-scale atmosphere can be created as a result of transformations in the fireball and the ensuing fires; in the event of widespread environmental disruption, gases released by the decay of dead plants or the altering of present activities may also alter the global environment.

Initial concern about what nuclear weapons might do to the global atmosphere goes back to a calculation performed in 1943 by Konopinski and Teller to determine whether a chain reaction might accidentally be set off "that would encircle the globe in a sea of fire."[17,18]

The matter next arose in the early 1970s in a serendipitous fashion. Environmental analyses of the potential climatic effects of a fleet of supersonic aircraft led to recognition that nitrogen oxides (primarily nitric oxide and nitrogen dioxide) emissions could reduce stratospheric ozone.[19,20] As a test of this hypothesis, Foley and Ruderman[21] pointed out that of order 10^{32} molecules of nitric oxide were created per megaton explosion[22] because the rapid expansion led to cooling that quenched the reformation of N_2 and O_2, just as in an internal combustion engine. They then calculated, assuming that stratospheric chemistry would be in equilibrium, that the nitric oxide created during the nuclear test series in the early 1960s should have reduced stratospheric ozone by about 15%. Because this was not in agreement with the few percent reduction seen in the observations, they suggested that understanding of stratospheric ozone chemistry was not correct. (They turned out to be right, but for the wrong reason.)

Time-dependent calculations of the nitric oxide injections from the test series soon showed that only a several per cent effect should be expected. (That this near agreement occurred was somewhat fortuitous given the changes since that time in rate coefficients and the need to include chlorine chemistry.) In the course of carrying out the test series calculations, Julius Chang[23] accidentally misplaced a decimal point and calculated the effect on stratospheric ozone of a 100,000 Mt injection (rather than a 100 Mt series of tests) and wiped out the ozone layer. He decided then to calculate what a nuclear war would do to the ozone layer. Calculations by Chang[23] and independently by Hampson[24] led to a National Academy of Sciences review in 1975.[7] Their analysis suggested that a 10,000 Mt war involving the many multi-megaton weapons characteristic of arsenals at that time would loft of order 50 million tonne of nitric oxide to the stratosphere, which would lead to a reduction of the Northern Hemisphere stratospheric ozone loading of order 50% with a recovery time of several years. If the 10^{32} molecules/Mt injected in a 10,000 Mt war destroy 50% of the Northern Hemisphere ozone, each NO molecule has destroyed about 2×10^4 molecules of ozone (assuming no production). This high effectiveness of NO destruction of ozone results from a catalytic cycle in which

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$
$$\text{Net} : O + O_3 \rightarrow 2\ O_2.$$

These reactions proceed until the nitrogen oxides are removed from the stratosphere by transport processes or tied up chemically, both of which are relatively slow processes. Although increased incidence of skin cancer (melanoma) is the normal concern from decreasing ozone levels, that is believed correlated with the integral lifetime dose. For large perturbations, it is the acute phase that is of concern. A 50% reduction would increase the intensity of solar ultraviolet radiation reaching the surface sufficiently to lead to skin blistering in tens of minutes, an effect, it was felt, that could also significantly impact many plants and animals, including humans as they ventured out seeking food.

As nuclear arsenals changed in the 1970s, the ozone problem ameliorated. The MIRVing of strategic missiles reduced the yields of individual weapons to the few hundred kiloton range—a trend also dependent on improving accuracy—which meant that the nitric oxide would be injected mainly into the troposphere, well below the peak concentrations of stratospheric ozone at 25–30 km (Foley and Ruderman[21] estimate stabilized cloud top $C_T(\text{km}) = 22Y^{0.2}$ and cloud bottom $C_B(\text{km}) = 13Y^{0.2}$ where Y is yield in megaton). A recalculation of the effect on stratospheric ozone assuming nuclear arsenals of the mid-1980s suggested a reduction of 15–20% with recovery over a few years.*[11] Such an ozone reduction would lead to a few-fold increase in the ultraviolet flux, thereby threatening many sensitive species.[7,25] In that the annual ultraviolet erythema dose increases about 50-fold from the pole to the equator,[26] an increase of a few fold would not however, be an unsurvivable threat to humans.[27]

The recognition of the extent of fires has, however, again raised questions concerning potential perturbations to atmospheric chemistry. The fires themselves lead to nitrogen oxide and hydrocarbon emissions that, in the presence of sunlight, could create ozone and other oxidants. Calculations by Crutzen and Birks[12] suggested that ozone levels could reach 0.16 ppmv, exceeding air quality standards, but well below peak levels experienced in Los Angeles. Calculations by Penner[25] subsequently showed that, because the nitrogen oxide would be removed more rapidly than the smoke, the diminished light levels would not be sufficient to induce high tropospheric ozone levels. Of course, while removal of the nitrogen and sulfur oxides created by the fires limits the tropospheric chemical changes, it will acidify the precipitation, causing what has been referred to as the "nuclear pickle."

The smoke injections would also lead to climatic changes that would affect atmospheric chemistry. Smoke-induced absorption of solar energy, which could raise stratospheric temperatures by 50–100 K, would accelerate the Chapman photochemical cycle which destroys O_3. More importantly, the smoke-induced heating of the troposphere would cause a lofting of ozone poor tropospheric air into the stratosphere, displacing the lower stratospheric ozone reservoir upward to altitudes where it can be photochemically destroyed and carrying the fireball-created nitrogen oxides upward to levels where catalytic destruction can occur. The smoke particles themselves also serve as an ozone sink. The stratospheric displacement by tropospheric air in the Northern Hemisphere also would lead to a southward and downward displacement of the ozone rich air in the tropical and Southern Hemisphere stratosphere, possibly enhancing surface ozone values in the Southern Hemisphere.

Calculations of these many interacting fire-induced effects are just beginning, but it seems quite possible that stratospheric ozone reductions of 50% or more are possible. Interestingly, this again raises the potential for tropospheric chemistry changes, because the reduction in ozone optical depth in the ultraviolet is probably balanced by the increase in optical depth due to the smoke only over the first few weeks.[25]

There is a wide range of other possible chemical effects, many of which have not yet been explored. These include creation of pyrotoxics, build-up of

* An excursion case with 100 20 MT explosions led to a depletion of just over 40%, slowing the strong dependence of the effect on high yield weapons. It is interesting that while the trend toward lower yield weapons eased the ozone depletion effect, it exacerbated the global fallout effect by a factor of ten (although still significantly below harmful effects).

H_2S due to reduction in the oxidizing potential of the atmosphere, stratospheric chlorine and bromine injections from nuclear explosions over the oceans, carbon monoxide generation, and many more. Enhancement of the greenhouse gas potential of carbon dioxide emissions would be very small (combustion emissions are about equal to one year's fossil fuel emissions; decay of vegetation without regrowth could be a substantial contributor, but seems unlikely). At present, none of these many potential effects has been demonstrated to be significant, but that may only be due to arbitrary assumptions that have been made or aspects, particularly interactive aspects, that have been overlooked.

CONCLUDING REMARKS

Nuclear war would be a catastrophe of unprecedented proportions. The direct effects of fire and blast created by a major nuclear exchange could kill hundreds of millions, which has provided the compelling basis for avoiding nuclear war.

In addition to these direct consequences, and the very substantial disruption of the national and international social and economic fabric that would occur, a nuclear war would induce a series of environmental effects that would spread the impacts among combatant and non-combatant nations alike. Beyond regions of local fallout, global fallout would exert a relatively minor effect, unless a substantial fraction of the nuclear fuel cycle inventory were widely dispersed. Smoke and dust injections could seriously disturb the global climate, particularly the hydrologic cycle during the first several months, but depressing temperatures for of order a year. The combined fireball and fire emissions could significantly deplete stratospheric ozone, greatly impacting human activities and ecological systems for perhaps a few years.

If an additional reason to avoid war is needed, the environmental impacts will certainly be present. When "nuclear winter" was first interpreted as a freezing solid of the entire planet, there may well have been an additional and compelling moral imperative obvious to all to avoid the total annihilation of life. The present estimates do not encompass extinction, but they do indicate the potential for threatening a majority of the global population with starvation. Since the 1950s, the threats of fire, blast, destruction, and disruption have been sufficiently convincing; the potential environmental consequences substantially raise the ante for the non-combatants and, hopefully, will assure that deterrence is not simply a destructive threat between the superpowers, but is an active basis for responsible behavior among all nations.

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