Meteorol. Atmos. Phys. 38, 228-239 (1988)

Re-Analysis of the Nuclear Winter Phenomenon

S. F. Singer
George Mason University, Fairfax, Virginia. U.S.A.[*]

With 2 Figures
Received November 17, 1986
Revised June 5, 1987

Summary

An analysis of the report of the (U.S.) National Academy of Sciences (NAS) on atmospheric effects of a nuclear exchange leads to conclusions that differ from those of the NAS and of the earlier "TTAPS" and "AMBIO" studies. Any cooling of the earth's surface is likely to be *short-lived* because of rapid removal of the smoke clouds originating from nuclear burst-initiated fires, and *minor* because of appreciable greenhouse effects due to several distinct physical causes. (One of these, neglected in prior analyses, is the infrared absorption from cirrus clouds produced directly by the initial nuclear bursts.) Taken together, these effects may even induce slight surface warming ("nuclear summer") instead of cooling ("nuclear winter"). The consequences to atmospheric ozone are similarly ambiguous; depending on the detailed nuclear scenario, the net ozone content may increase – rather than decrease as argued by "TTAPS". Experiments could settle some uncertainties.

1. Introduction

A convenient way to analyze the atmospheric effects of a major nuclear exchange is by way of a critical examination of the National Academy of Sciences/National Research Council (NAS/NRC) report (1985. referred to in this paper as NAS). We will examine the logical consequences of certain NAS results that may have been ignored or inadequately treated in their report. We will concentrate on the physics of the phenomena and comment only briefly on nuclear scenarios. We can agree therefore to start with the NAS baseline case, even though it is not considered to be realistic by many experts. We ask:

(1) What are the physical consequences for the atmosphere of the NAS baseline case?

(2) Does a nuclear exchange really lead to substantial cooling of the earth's surface?

(3) Is the outcome robust to changes in the assumptions -- as has been claimed by Turco et al. (1983, referred to in this paper as TTAPS)?

Our re-analysis supports the following conclusions:

(1) The principal climate effects of a nuclear exchange are short-lived. .

(2) The effect on surface temperature should be minor; there should be neither deep freezes nor "quick freezes".

---

[*] Currently Chief Scientist, U.S. Department of Transportation, Washington D.C., U.S.A.

(3) There is even an appreciable likelihood of surface warming ("nuclear summer"); i.e., the outcome is not at all robust.

Our conclusions relate only to physical processes, not to ecological ones. For example, surface warming would have ecological consequences, although different from those of a freeze; cutoff of solar radiation would certainly stop photosynthetic activity.

2. Nuclear Scenario

The key parameters relevant to climate effects are the following:

(1) Are the nuclear explosions over urban or non-urban targets?

(2) Are they air bursts or ground bursts?

(3) Are they multi-megaton or sub-megaton bursts?

The NAS baseline case assumes a total yield of 6 500 Mt (megatons of TNT equivalent), not too different from the TTAPS baseline case (see TTAPS) of 5 000 Mt or the AMBIO case (1982) of 5 742Mt. All three assume that about one quarter of the yield would be expended against urban targets - 1 500 Mt for the NAS. (The significance of this key assumption is that urban areas contain much more combustible material per unit area and therefore generate more light-absorbing smoke than does the average non-urban area.)

However, this does not mean that all of the material will burn - and certainly not quickly. Kearny (1985) has pointed out cogently that the explosion's blast wave could snuff out many fires, and that a covering of rubble in modern cities will lead to smoldering fires lasting for days or weeks. This fact is of significance to the lifetime of the smoke particles, as we shall see later.

Small and Bush (1985) have analyzed non-urban target areas in some detail. Their smoke totals are only 1 to 20% of the corresponding TTAPS figures and would not lead to appreciable absorption of sunlight.

Singer (1984 a) has analyzed the particular case of snow-covered areas – relevant for winter scenarios, and especially for Soviet targets. Because snow reflects most of the light radiation from the burst, and in addition must be evaporated before ignition occurs, a 1 Mt burst which normally ignites out to 5 miles (Glasstone and Dolan, 1977) would typically ignite an area 20 times less – and none at all if the burst is more than 1000 feet above the surface.

The key assumptions in the three scenarios (NAS; TTAPS; AMBIO, 1982) all tend to maximize the yield of smoke and therefore climate effects; they all use urban targets and airbursts (75% in the NAS case). But a counterforce strategy (McNamara, 1977) would target missile silos to reduce and prevent a response to a first strike. It would employ ground bursts against hardened targets, rather than air bursts that ignite a wider area. It would also employ megaton weapons rather than sub-megaton weapons and thereby put more dust and water vapor into the stratosphere than shown in the NAS report.

In spite of objections to the basic NAS scenario and to the details of bomb yields and burst altitudes, we will proceed in the following to investigate as fully as possible the physical consequences of the NAS baseline scenario.

3. Atmospheric Effects: Overview

The discussion can be divided into distinct parts:

1. The *nuclear burst effects* that occur during the first hour or so following the nuclear detonations. (The salvo of several thousand detonations is assumed to occupy a similar time frame.) The immediate effects of the fireball include the lofting of dust (i.e., pulverized soil and debris); the vaporization and lofting of surface water, including also ambient atmospheric water vapor; the creation and lofting of nitrogen oxides (NO_x). These immediate effects are described in the NAS report. The later effects, not dealt with in the report, include the condensation of the water vapor and the possible formation of cirrus clouds. The effects of NO_x on ozone are also more complex and likely quite different than described in NAS and TTAPS.

2. The *generation of smoke* from fires ignited by the nuclear bursts. This phase may occupy a few hours to a few days. Of particular interest is the spatial distribution of the smoke particles, including the vertical injection profile, and the subsequent horizontal movement and dispersion. Even more important are physical changes in the particles, especially agglomeration, that lead to reduced optical absorption (per unit mass), a relative increase in infrared absorption, and more rapid fall-out. These phenomena are not adequately treated in NAS and TTAPS, but affect a) the lifetime of an appreciable smoke cloud, and b) the non-uniformity of the cloud. In fact, one may question whether the lifetime is sufficient for the initially quite non-uniform cloud even to approach uniformity (Singer, 1984b, 1985). Most of the modeling used so far has either been one-dimensional (1-D) (NAS, TTAPS) or global-scale, 3-dimensional (3-D), (Aleksandrov and Stenchikov, 1983; Covey et al., 1984), and therefore not equipped to deal with smoke removal problems by rainout that require a meso-scale or even cloud-scale approach (Singer, 1984c; Paltridge and Hunt, 1984).

3. The *atmospheric ozone content and distribution.* Contrary to the NAS report and TTAPS, nuclear bursts and subsequent fires may enhance rather than diminish ozone. The situation is vastly more complex than indicated in these references. The large amounts of water vapor and hydrocarbon created and lofted play an important role in the complete ozone chemistry. In any case, if stratospheric ozone were to be destroyed, then the effects of the solar ultraviolet radiation penetrating into the tropospheric smoke cloud must be fully considered, including the effects of chemical changes and of the electric charging of smoke particles.

4. The *change* in *surface temperature,* generally described as a substantial temperature decrease (NAS) or even as a "nuclear winter" (TTAPS). Contrary to the general view, we find an appreciable likelihood for surface warming and an even greater likelihood of a minor cooling - hardly the nuclear winter predicted in TTAPS. We discuss the surface temperature effects of the following cases, using simplified 1-D models:
(a) Non-uniform smoke clouds; the "quick freeze" issue.
(b) Low-altitude smoke clouds, with optical parameters given by NAS and TTAPS.
(c) Effect of a stratospheric cirrus layer.
(d) High infrared opacity of the smoke clouds due to various physical factors.

Finally, we discuss the significance of such surface temperature changes from a purely climatological point of view.

4. Nuclear Burst Effects

Dust: In the *NAS* baseline scenario 6 500 Mt are exploded, with 1 500 Mt of ground bursts. Only ground bursts create dust, about 0.3 teragrams (1 Tg= 10^{12} g= 10^9 kg= 10^6 metric tons) per Mt (NAS, p. 17). Therefore, 450 Tg of dust are lofted, of which 40Tg are assumed of submicron size, capable of remaining in the atmosphere for some length of time. The bulk of the dust particles, ~ 410 Tg, will fall out quickly, depending on the dust-size distribution.

Effective lofting into the stratosphere requires an explosion yield above roughly 1 Mt (Glasstone and Dolan, 1977; and p. 17 of NAS), in contradiction to Turco et al. (1985). The NAS report places 15 Tg of submicron dust into the stratosphere (p.31). We estimate their number as ~ 7 x 10^{27}; they serve as possible condensation nuclei for cirrus.

Water vapor (WV): There are several sources of the H_2O lofted into the atmosphere by the nuclear bursts:
(1) Ground water and mineralized water of hydration would be released and lofted by a surface burst (NAS, p. 101)
(2) Entrained ambient water vapor would amount to 0.1 to 1.0 Tg/Mt.
(3) An additional large source, estimated (NAS) as < 3 Tg/Mt, would come from ground bursts at or bordering lakes, estuaries, or oceans.

The NAS report (p. 101) uses 1 Tg/Mt. For the baseline scenario one would get (1 500 Mt) (1 Tg/ Mt) + (5 000 Mt) (0.5 Tg/M t) = 4 000 Tg, in line with the NAS value of less than 6000Tg. Most of the liquid water will have been vaporized in the fireball and carried into the upper troposphere and stratosphere. There the concentration of H_2O would be ~ 10^{-3} kg/m^3, leading to the formation of ice crystals (high-altitude cirrus) (NAS; p. 163).

Additional sources of water vapor come from the fires following nuclear bursts: water of combustion, evaporated surface water, and entrained water vapor. The NAS report (p. 102) uses a mean value of 5 kg of H_2O/kg-burned, of which about 1 to 2 kg is "new" water and the remainder a redistribution of ambient water vapor. The baseline scenario leads to a total amount injected into the troposphere of 40 000 Tg. The column abundances in fire clouds could thus be 1 to 5 kg/m^2, compared to about 10 kg/m^2 in natural cumulus clouds and 0.01 to 0.1 kg/m^2 in cirrus clouds (NAS). But note that the NAS report assumes here an area of (8 to 40) x 10^{12} m^2, about 1.6% to 8% of the earth's surface. The *initial* area of significant fire clouds is likely to be about 5 x 10^{11} m^2, corresponding to 1 000 cities of 500 km^2 each. This would lead to initial column abundances of water vapor many times greater than natural cumulus clouds, thus making rainout of smoke highly probable.

Cirrus: The strong optical (and especially infrared) effects of ice crystals are briefly mentioned but not followed up in the NAS report – and not at all considered by TTAPS. A more detailed treatment is in order.

The initial H_2O lofted is 4 000Tg, into an area perhaps 0.1% of the earth's surface (10^{-3} x 5.1 x 10^{14} m^2), leading to a column density of ~ 10 kg/m^2. The ambient density above 11 km is only 4 800Tg/(5.1 x 10^{14} m^2) ~ 0.01 kg/m2 (derived from Table 5.2-1 of NAS). The ambient density above 5 km is known to be 5 x 10^5 Tg/ (5.1 x 10^{14} m^2) ~ 1

kg/m^2. There is thus no question that the nuclear bursts alone (not counting the fires) would increase local ambient densities in the upper troposphere and stratosphere by a factor of 10 or more. The additional H_2O from fires, 4×10^4 Tg, *if lofted above 5 km by fire plumes*, would raise the increase by another order of magnitude, to 100 times ambient above 5 km altitude.

To ensure the formation of ice crystals one needs to verify the degree of supersaturation created by the injection of the additional H_2O. The saturated mixing ratio (in units of grams of water vapor per kg of air) is given (Johnson, 1954, p. 381) as:

$$w_s = 622\ e_s/p \qquad (1)$$

where e_s is the saturation water vapor pressure and p is the ambient pressure. At the tropopause level, $w_s \sim 0.05$ g/kg or 50 ppm (by weight) (Johnson, 1954).

The NAS report (p. 103) gives the ambient water vapor mixing ratio at 12 km as 11 ppm, corresponding to a concentration of $\sim 3 \times 10^{-6}$ kg of H_2O/m^3. The ambient stratospheric water vapor content is given as 5 000 Tg. Therefore injection of 4 000 Tg (if uniformly distributed) would double the ambient H_2O content, but increase it by as much as a factor of 1 000 (i.e., ~ 200 times saturation) if injected into an area as small as 10^{-3} of global area. Sublimation of the ice crystals would occur only once diffusive expansion has reached a factor of 200. One may use other data, for example injected material from volcanoes, to obtain an idea of the time scale of expansion.

It is of considerable importance to define the lifetime of these ice crystals created by the nuclear bursts relative to the lifetime of the smoke particles created by the subsequent combustion. As discussed later, the higher-altitude ice clouds, after horizontal spreading, will produce a strong greenhouse effect that may overcome and even reverse the cooling effects due to the absorption of solar radiation by the smoke cloud.

Another problem is to consider explicitly the effects of the H_2O injected by the combustion processes. Water vapor may not condense in the smoke layer, which is assumed to be quite hot (NAS, TTAPS), but it will add to the greenhouse effect.

5. Combustion Effects

The major topic of this re-analysis is the effect of a nuclear exchange on the earth's surface temperature. And the major factor is the generation of light-absorbing smoke in the multitude of fires ignited by the nuclear explosions.

We have already discussed how scenario-dependent the amount of smoke is. It depends on the nuclear strategy, on the time of the exchange (season, weather conditions), and on the detailed geography. Nevertheless, we will assume here the NAS baseline value for the amount of smoke put into the atmosphere, 180 Tg (of which 150Tg is urban) -compared to 200 Tg/y (of low-altitude smoke) from normal sources. We also accept all of the precedent assumptions, including the important one setting the degree of immediate rainout of smoke particles. We will concentrate on five physical aspects of the smoke problem, deferring the optical properties and their significance until later.

a) The initial geographic non-uniformity of the smoke clouds.

b) The lofting process and the eventual altitude of the smoke clouds; its significance to the atmospheric lifetime of smoke.

c) The smoldering of fires and its significance.
d) The effect of horizontal winds on smoke altitude.
e) The possibility of further smoke lofting by solar heating.

(a) There is no question that the smoke sources are discrete rather than uniform, and that therefore the initial smoke plumes cannot be uniformly distributed. TTAPS and other investigators (Aleksandrov and Stenchikov, 1983; Covey et al., 1984) have glossed over this important issue by starting their calculations with a geographically uniform smoke layer (at least over the latitude band of 30° N to 70° N). There are three points to be made here:

(i) In the *TTAPS* baseline scenario the amount of smoke is 225Tg and just adequate to produce an optical depth τ of 3.0, corresponding to 95% absorption of sunlight, over the critical latitude band of 30° N to 70° N. The NAS report (p. 81) arrives at similar values, 150 Tg for urban fires, plus 30Tg for non-urban (mainly forest fires). Note that these values are just right to lead to surface cooling (if one were to accept all the other TTAPS assumptions). For if the amounts of smoke were much greater, saturation occurs: absorption would increase towards 100%, but the infrared opacity would become appreciable and delay the cooling; and if the amounts of smoke were less and at low altitude, then surface *warming* would result (TTAPS, p. 1286). (See also Table 1.)

(ii) The atmospheric survival lifetime of the smoke may not be long enough to ever reach a substantial degree of uniformity. Patchy clouds, with smoke content greater than required for effective cutoff of solar radiation, will not produce significant cooling. If we assume, for example, that initially 1% of the earth is covered by smoke patches or plumes, then solar radiation will penetrate to the surface 99% of the time. Advection of warm air and the small but finite heat capacity of the soil should prevent "quick freezes". More important even, the optical thickness will exceed 3.0, reducing the effectiveness of the mass for solar absorption because of saturation. Substantial climate effects require a substantial degree of uniformity, unless the amounts of smoke generated exceed by a large factor even the most extreme estimates made.

In this connection, Stothers' analysis of the 536 AD volcanic eruptions shows (extinction) optical depths of between 2.2 and 2.5 (90% reduction of solar insolation) for about a year, but no freezing surface temperatures (Stothers, 1984).

(iii) Neither the 3-D (Aleksandrov and Stenchikov, 1983; Covey et al, 1984) nor indeed the 1-D models (NAS, TTAPS) used so far are equipped to deal with the problem of establishing the time scale to reach substantial uniformity of the smoke cloud. Mesoscale (or even cloud-scale) effects not incorporated in 3-D models dominate the dispersion, but also can lead to enhanced rainout of the smoke particles (Singer, 1984c; Paltridge and Hunt, 1984).

An additional source of removal of smoke particles is the scavenging by the large amounts of dust previously put into the atmosphere by the nuclear bursts themselves. Approximately 410 Tg of micron-sized (or larger) dust will fall out quickly and add to the smoke sweepout produced by rain droplets and especially snow flakes. If the dust fallout is confined to about 10% of the earth's surface, then an areal density of 10^{-2} kg/m^2 results. Assuming a typical dust diameter of 10 microns and mass of 10^{-12} kg, this density corresponds to 10^9 particles/m^2 or a surface area of 1 m^2/m^2. Even if dust fallout covers a larger area, it must play a role in smoke removal.

(b) The crucial parameter to a full nuclear winter effect is the lofting height of smoke. If this height is below 5 km, then the lifetime may only be a few days (NAS, p. 4). At heights of 9 to 10 km, assuming negligible moisture at that altitude, halflife of smoke particles is stated to be > 30 days (NAS, p. 4). But this estimate must be high since it neglects the water vapor lofted earlier by the nuclear explosions: ~ 4 000 Tg spread over an area 10^{-3} of earth surface, therefore ~ 10 kg/m^2. Once one adds combustion water, 8 500 Tg, and water sucked in, ~ 40000Tg (NAS, p. 102), then the water content of the fire clouds is 10 – 50% that of cumulus clouds (NAS, p. 102). The enhanced local concentration of water vapor should also enhance rainout of smoke in the altitude range 5-9 km. Convective activity within the smoke cloud should further enhance the possibility of water vapor condensation, smoke particle agglomeration, and rainout.

Some of these points have been tested for the case of the Dresden firestorm. The observed absence of sufficient darkness leads to either smoke emission factors lower than in NAS, TTAPS, AMBIO (1982), and/or extensive coagulation of smoke particles, and/or efficient removal of smoke in self-induced rainfall ("black rain") (Peczkis, 1988).

Even if there were no rapid rainout of smoke from above 5 km, can appreciable amounts reach those levels? In the NAS report (NAS, p. 74) the only theoretical support comes from the use of a simple plume equation which gives:

$$Z_C = 0.2\ Q^{1/4} \qquad (2)$$

where Z_C is the height in km, and Q is the heat source in megawatts (typically 1 000 MW). To get a smoke altitude of 10 km, the NAS report extrapolates by over 3 orders of magnitude to Q = 6 x 10^6 MW, and from the diameter of smoke stacks to city fires covering 100 km^2 of area, with burning times of 10^4 sec. Implicit in the extrapolation is neglect of turbulence in the burning, of entrainment of cool air and water, of horizontal cross winds, and of smoldering, and the assumption of merging of all fires in the 100 km^2 area.

(c) It should be noted that smoldering does not add to the total amount of smoke, as erroneously supposed by Turco et al., (1985), who double-counted. On the contrary, smoldering reduces *Q* (and therefore Z_C). Assume in the example (NAS, p,74) that half the combustible material smolders for about 10^6 sec. According to the plume equation, the initial burn now reaches an altitude of 8 km (with only half the amount of smoke); the remainder of the smoke reaches only 2.7km altitude and presumably rains out in a few days.

(d) The sensitivity of the vertical distribution to horizontal winds can be clearly seen from recent buoyant plume calculations at Livermore (Penner et al., 1985). Using initial conditions comparable to the NAS scenario, most of the model calculations put the bulk of the smoke cloud between 2 and 4 km and none above 8 km (see Penner et al., 1985, Fig. 10). For comparison, NAS shows appreciable smoke cloud absorption up to about 15 km and TTAPS well beyond that level (see NAS, Fig. 7).

(e) It has been assumed so far that the smoke is lofted by the thermal energy of the fire; an additional lofting mechanism mentioned (NAS, p. 75) is based on solar heating of the smoke. This mechanism is clearly beyond a strictly one-dimensional model. Since the particles themselves are not buoyant, even if hot, the atmosphere (and hence smoke-layer) expands during the day, but should contract at night. The one-

dimensional treatment thus corresponds to a "breathing" of the atmosphere without any physical consequences.

More recently, Malone et al. (1985) has examined solar lofting in a three-dimensional model and found a "bootstrapping" effect whereby an initially low-altitude smoke cloud can climb in altitude and thereby extend its lifetime greatly. This process bears closer examination.

(i) The model does not yet simulate the day-night cycle, but assumes a diurnally averaged sun. It therefore does not show any nocturnal cooling and downward motion.

(ii) We have established that the lofting process does not work in one dimension; nor can the smoke cloud be lifted as a sheet. To be physically realistic, the process must be examined on a mesoscale (or even cloud-scale) basis, i.e., with convection, turbulence, and possible water-cloud formation included. For example, a narrow smoke plume heated by the sun creates a strong horizontal temperature gradient inducing local circulation that drives smoke particles in various directions, including downward. Even a (hypothetical) initially uniform smoke layer would develop instabilities as it is heated. Present 3-D models are not yet able to simulate such effects.

(iii) The initial plumes are quite non-homogeneous, a few thousand patches of perhaps 100 to 1000 km^2 each (a total area of $\sim 10^6$ km^2, compared to the earth's surface area of 5.1×10^8 km^2). If the eventual uniform optical thickness in the latitude band 30° N to 70° N is to be 3.0 (TTAPS), then the initial optical thickness will be as much as 1500. Because of the great optical depth, only the top of the plume will be heated, say, up to $\tau = 3$; therefore, only a few percent of the plume will be lofted, with the rest remaining in darkness.

6. Ozone Layer and Related Problems

According to TTAPS and the NAS report, the baseline nuclear exchange will result in destruction of stratospheric ozone, increased UV radiation at the surface (after the smoke is dissipated), and severe biological and health effects for some two years. These statements are out-of-date wisdom and not in accord with our current understanding. For example, they ignore the role of the abundant water vapor in the photochemistry, as well as the role of heterogeneous reactions on the dust particulates injected by the nuclear explosions and the smoke injected by the subsequent burning.

Most important, it has now been known for several years that nitrogen oxides increase ozone in the upper troposphere and lower stratosphere, while decreasing the concentration in the upper stratosphere. The net effect on the ozone column is therefore quite scenario-dependent. This can be seen, for example, from Table 6.1 of the NAS report (NAS, p. 109) where the AMBIO scenario leads to no ozone column depletion.

One should in addition take account of the prolific hydrocarbon generation in the combustion, estimated at 45 Tg of methane and 45 Tg of non-methane HC (NAS, p. 110). One therefore obtains photochemical smog generation, with substantial ozone enhancement above the smoke layer - hardly the effects envisaged by TTAPS. The importance of hydrocarbons and tropospheric NO_x may be deduced from the summary conclusions of a group of experts (NASA/Dpt. Transpt., 1984):

"(9) Calculations using realistic scenarios for projected increases in atmospheric concentrations of chlorofluorocarbons, NO_x,N_2O, CH_4, and CO_2 predict ozone column

increase to dominate for the next few decades. For scenarios in which CH_4 is assumed to be constant at today's level, the ozone column is predicted to decrease after this initial period. A major uncertainty in the predicted evolution of the ozone column beyond the next few decades arises from the very uncertain future course of atmospheric methane (CH_4) concentrations, i.e., if atmospheric CH_4 continues to increase at a substantial rate, the combined effect of CH_4 and fluorocarbons may never result in a decrease in column ozone.

(10) One of the reasons for an ozone increase in the near-term scenarios is the predicted increase in tropospheric O_3 from the NO_x injected into the upper troposphere and lower stratosphere by subsonic aircraft. These predictions are more uncertain than those for the middle and upper stratosphere, because of the localized nature of the NO_x source coupled with the rather crude treatment of transport effects in the predictive models."

If a substantial depletion of stratospheric ozone were to occur, then the discussion of the physics in the TTAPS and the NAS reports is quite incomplete. One would have to consider the consequences of a substantial flux of middle-UV photons (~ 2 500 Å = 250 nm) into the troposphere, especially the resultant photochemical effects and electrical charging effects on smoke particles. We are dealing with ~ 5 eV photons, energetic enough to photo-detach electrons from particles. The resultant dynamic effects, whether they cause more rapid coagulation or not, should be of some importance in the evolution of the smoke cloud. It may be possible to investigate this point in a laboratory simulation, using mercury vapor arc lamps and injected smoke particles.

7. Surface Temperature Effects

For the purpose of discussing the atmospheric physics of the problem, we will accept the amounts of smoke given by TTAPS and by the NAS report. We note, however, that different (and some would argue - more realistic) scenarios produce from 5 to 100 times less smoke; as little as a fivefold reduction would effectively invalidate the "nuclear winter" effect, even with the use of the TTAPS model and all other TTAPS assumptions.

We also note the TTAPS assumption, repeated in the NAS report, of negligible IR opacity for the smoke particles, a factor of 10 less than the optical opacity. This assumption, of course, permits the direct radiation of much of the surface heat out into space, and makes the problem similar to the nocturnal cooling of a desert surface – except that here the "night" can last many days or weeks.

We now discuss the surface temperature for different cases.

7.1 Non- Uniform Smoke Clouds

When the smoke is non-uniform, covering, say, 1% of the 30° to 70°N latitude band, then the optical thickness τ_{vis} must be ~ 3.0/0.0l = 300. Since saturation sets in for $\tau > 3.0$, solar radiation will remain cut off, But the IR optical depth will now be 30.0, assuming the low ratio of 0.1 between IR and optical opacity (TTAPS) – quite sufficient to slow down the cooling of the surface. In addition, these thick clouds will have embedded in them large amounts of water vapor and other radiatively active gases from the combustion process. Further, since the patches cover only a fraction of the globe, initially

only 1 %, each point on the surface will experience only a slight diminution of solar radiation – averaged over time. With a reasonable heat capacity, the surface will not cool appreciably, nor would it experience a hypothesized "quick freeze" (Covey et al., 1984).

7.2 Greenhouse Effects

A low-altitude smoke cloud, in addition to having a very short lifetime, will also be subject to the normal greenhouse effect from overlying radiative gases, such as CO_2 and H_2O.

The problem can be treated by simple one-dimensional radiation models (Cess, 1985; MacCracken, 1985). Even though incomplete and necessarily inaccurate, they lend

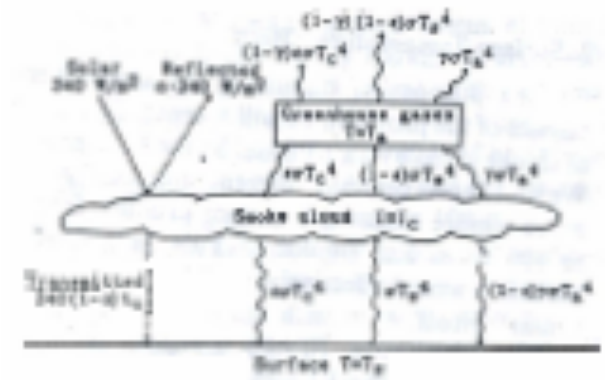

Fig. 1. Illustration of a simple, 3- level equilibrium climate model (after MacCracken, 1985)
~~IR radiation. ---- Solar radiation. T_c Temperature of smoke cloud. T_a Temperature of atmosphere above smoke cloud. T_s, Surface temperature. *a* Albedo. t_c Fraction of incident solar transmitted through smoke. ε Fraction of incident IR absorbed by smoke. *γ* Fraction of incident IR absorbed by greenhouse gases

themselves well to comparative sensitivity analysis. A particularly simple 3-level equilibrium climate model, by M. MacCracken (1985), is shown in Fig. 1. The solution for the surface layer temperature, T_s, is given by (see also Table 1):

$$\sigma T_s^4 = 340\,(1 - a)\,[\gamma/(2 - \gamma) + (1 + t_c)/(2 - \varepsilon)] \qquad (3)$$

Table 1. *Surface Temperature T_s Calculated for Different Model Parameters*

	a	t_c	ε	γ	T_s
"Planetary" (no atmosphere, no smoke)	0	1.0	0	0	5°C
	0.3	1.0	0	0	-19°C
Ambient (normal greenhouse, no smoke)	0.3	1.0	0	1.0	30°C
TTAPS (high altitude smoke cloud)	0	0	0	0	-39°C*
(low altitude smoke cloud)	0	0	0	1.0	35°C
TTAPS + high IR opacity high altitude smoke cloud	0	0	1.0	0	5°C
+ high IR opacity low altitude smoke cloud	0	0	1.0	1.0	58°C
TTAPS + cirrus	0	0	0	(see text)	>35°C
+ reflecting cirrus	0	0	0	(see text)	>15°C

*Only the extreme TTAPS case produces freezing temperatures, by neglecting any possible greenhouse effects.

(i) The "planetary" temperature, without atmosphere and surface albedo, i.e., with $\gamma = 0$, a = 0, and with no smoke, i.e., $t_c = 1$, $\varepsilon = 0$, is 278 K.

(ii) The "ambient" temperature, with nominal greenhouse effect and albedo, i-e., $\gamma = 1$, a = 0.3, is calculated from Eq. (3) as 303 K, about 15 K warmer than global mean. It is 25 K higher than the planetary temperature without atmosphere. If the bare earth had a surface albedo of 0.3, then the planetary temperature would be 254 K, or 49 K less than is obtained by adding the normal greenhouse effect.

(iii) The TTAPS case considers the greenhouse effect absent and zero albedo, i.e., $\gamma = 0$, a = 0. With a smoke cloud that is fully light-absorbing but not IR absorbing, i.e., $t_c = 0$, $\varepsilon = 0$, they would obtain 234 K, 44 K less than the planetary and 69 K less than the ambient temperature.

(iv) If one adds the normal greenhouse effect however, i.e. $\gamma = 1$, by considering the cloud to be at low altitude, T_s becomes 308 K, warmer than the TTAPS case (iii) by 74 K.

Enhanced greenhouse effects should be present from the injection of additional radiative gases into the normal atmosphere.

We have already noted the copious injection of water vapor and nitrogen oxides to high altitudes by nuclear bursts. Further, as discussed earlier, the column density of ozone may be enhanced rather than reduced; especially with a nuclear scenario of sub-megaton bombs that inject NO_x into the tropopause region. Ozone has strong absorption bands in the IR window region, near 10 μm, which should increase the normal greenhouse effect. In addition, the IR energy radiated by the ozone will be low, coming from near the tropopause temperature minimum; this feature further enhances the greenhouse effect.

High-altitude cirrus is important because of the strong IR absorption of ice (especially dirty ice) near 10 μm (and out to 100 μm), ~ 100 to 200 m^2/kg for particles of size of a few micrometer (Bergstrom, 1973). A cirrus layer will produce a strong greenhouse effect for even a high-altitude smoke cloud. For the case of a low-altitude smoke layer, where cirrus absorption can fill in the narrow atmospheric window region (8 to 12 μm), the temperature increase can be very high and will depend crucially on the details of the remaining window, i.e., on the thickness and spatial homogeneity of the cirrus cloud. For a high-altitude smoke layer the cirrus effect is less important.

For unexplained reasons, the NAS report (p. 163) considers only the water of combustion diffusing or convecting out of the smoke cloud, but not the water lofted by the nuclear bursts themselves. As discussed earlier, the initial water vapor lofted above the tropopause is 4 000 Tg = 4×10^{12} kg, into an area of perhaps $10^{-3} \times (5.1 \times 10^{14}\ m^2)$; therefore, the surface density is 10 kg/m^2, over a thousand times greater than the NAS value of 0.007 kg/m^2 (NAS, p. 163). A larger area would lead to lower surface densities, reducing the degree of supersaturation from 200 to lower values, but not changing our major conclusion.

Assume a cirrus particle of dimension 1 μm and mass 5×10^{-16} kg. A surface density of 10 kg/m^2 translates into 2×10^{16} particles/m^2. With particle cross-section of ~ 10^{-12} m^2, we have 2×10^4 m^2/m^2, more than enough to cover. A realistic procedure would be to cover the 30° to 70° latitude band, providing an areal coverage of 80m^2/m^2. Even

with full dispersion of the cloud, a factor of 1 000, the areal coverage is 20 m^2/m^2, much greater than one.

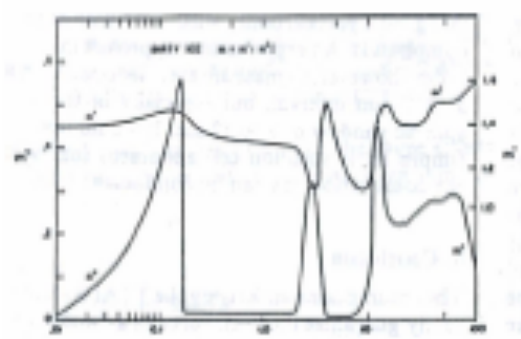

Fig. 2. Dirty-ice complex refractive indices are used in model computation (after Greenberg. 1968)

A more refined calculation does not change this result greatly. The complex refractive index of dirty ice is given as $m = 1.3 - 0.001i$ in the visible, and as $m = 1.4 - 0.4i$ in the infrared at 10 μm (Greenberg, 1968) (see also Fig. 2).. In the infrared, for a « λ, the absorption efficiency Q_{abs} (defined as actual absorption cross section divided by the geometric value) is given (Greenberg, 1968) as:

$$Q_{abs} = 8\pi(a/\lambda)\, \mathcal{J}\, (m^2 - 1) / (m^2 + 2) \qquad (4)$$

where $\mathcal{J}$ is the imaginary part of the bracketed term. For a=0.5 μm and λ = 10 μm; $Q_{abs} \sim 0.2$. The absorption cross-section per unit mass, k_{abs}, is 2 000 m^2/kg x 0.2 = 400 m^2/kg. The initial optical depth, corresponding to the 10kg/m^2 loading value, is 400; after uniform dispersion into a latitude band, the optical depth is still as high as 2.0.

For comparison, we note the value for the extinction cross-section (i.e. absorption plus scattering), calculated by Penner for $m = 1.75 - 0.3i$ and a lognormal size distribution. For a mode diameter of 1 μm and standard deviation of 1.5 (i.e., for a ~ λ), k = 2 000m^2/kg; for a mode diameter of 0.1 μm, *k* rises to 10^4 m^2/kg (MacCracken, 1985).

Albedo: The high value of the real part of the refractive index suggests the possibility of a high albedo of the cirrus layer that may reflect a portion of the incident visible solar radiation back out into space and thus overcome at least part of the enhanced greenhouse effect. An upper limit of albedo may be estimated by the use of Henyey-Greenstein functions (Van de Hulst, 1980) for a particle scattering albedo of 1.0. For conservative scattering (i.e. no absorption in the optical range), and asymmetry parameter $g = 0.75$, the reflected energy is greater than 90% for optical thicknesses τ greater than 64. But after the cirrus cloud disperses, thinning to, say, $\tau \sim 2$, the value of reflected energy falls to about 30% (for all but near-grazing solar zenith angles). For a smaller particle single-scatter albedo, say 0.8, the reflected energy is only about 20 to 30% for values of τ from about 1.0 up to infinity.

The temperature effect of a 25% reduction in the solar radiation input can be roughly estimated as $(1 - 0.75^{1/4})$, or about 0.07 x 300K, i.e. a 20K reduction – small compared to the enhanced greenhouse effect of the cirrus cloud. (See Table 1.)

Tests: It would, of course, be useful to verify these estimates experimentally, by examining data from Pacific bomb tests conducted during the 1960's. W. W. Kellogg (private communication, August 1986) recalls visual observation of heavy cirrus following the fireball's ascent.

A 1 Mt burst above a water-surface should loft 3 Tg tons of H_2O into the lower stratosphere, into an initial area of perhaps 300 km^2. The resultant surface loading, 10 kg/m^2, closely simulates the value for a nuclear exchange. With supersaturation of about 200, a cirrus cloud should form whose IR and optical properties can be followed as it travels, diffuses and sublimates. As far as surface temperatures are concerned, a passing cirrus cloud should produce its strongest effect on the nocturnal cooling curve of a desert surface.

Lifetime: The lifetime of the cirrus particles needs to be considered from the viewpoint of fallout and of sublimation. The water vapor will readily nucleate on the dust particles lofted by the same nuclear explosions. With 7×10^{27} particles, the average mass of an ice crystal is $[4 \times 10^{12}/(7 \times 10^{27})]$ or 6×10^{-16} kg, and the size less than 1 micrometer. Such ice crystals will not readily fall out. The number of nucleation centers is large enough to prevent the growth of crystals to much larger sizes; therefore, any comparison to the short lifetime of cirrus from tropical cumulus clouds may not be valid.

The ice particles will sublimate, at a rate which depends on the degree of dilution, and therefore on the time of dispersal. But as long as the surface densities are appreciable, 1.0 m^2/m^2 or greater, the particles will exercise a strong IR greenhouse effect.

7.3 *High IR Opacity of Smoke Cloud*

If the smoke layer is opaque in the IR region, then the surface may become quite warm. This case can be analyzed simply by considering the smoke layer as a "virtual" surface above the solid earth surface that absorbs all visible radiation but emits IR. (In the absence of water clouds, its albedo would be low and its temperature higher than the earth surface would be without the smoke layer.) The high-temperature virtual surface also radiates to the solid surface below. By the principle of detailed balancing the solid surface must reach the same high temperature as the virtual surface (the smoke layer).

Examination of Fig. 1, for the case $\varepsilon = 1$, shows a simple radiative exchange between the layer and surface, until temperature equality is obtained. This temperature is calculated to be 331 K for the case of a normal greenhouse effect, i.e. $\gamma = 1$; and 278 K for the case of a high-altitude smoke layer, i.e., $\gamma = 0$. We conclude, therefore, that a high IR opacity of the layer, even without any greenhouse effect, will produce a temperature 44 K higher than the TTAPS case (of 234 K), but a surface cooling of 25 K from ambient. (See Table 1.)

We now develop arguments as to why a high IR opacity is reasonable:

(i) The particle size distribution may have a larger median value than assumed by TTAPS. Ramaswamy and Kiehl have discussed such cases (1985). Agglomeration leads to larger particles; smoldering enhances formation of such large particles.

(ii) Even if the smoke particles are small (< 0.1 μm), they conduct their heat energy to an atmospheric layer that can become a strong IR radiator because of the addition of radiative gases: the water vapor and the complex organic molecules produced in the combustion process. Additionally, one has to take account of nitrogen oxides from the earlier nuclear bursts. As long as these gases and smoke particles occupy a similar region in space and maintain close thermal contact, we may consider the smoke particles to be effective IR radiators.

(Even in the absence of radiative combustion gases there would be substantial emission, but confined to the infrared absorption bands of ambient CO_2 and H_2O in the hot smoke layer.)

Any detailed quantitative analysis is prohibitive. The NAS report (pp. 110 – 112) suggests the release from the baseline combustion of some 90Tg of hydrocarbons, with over 200 different compounds. An experimental approach may be in order, however, to measure their IR opacity in the 5 to 50 μm interval, but especially in the atmospheric window of 8 to 12 μm. It would involve a simple IR absorption cell apparatus into which the combustion gas can be conducted.

8. Conclusion

The assumptions underlying the TTAPS study virtually guarantee the occurrence of a "nuclear winter": (i) sufficient smoke to cut off nearly all sunlight; (ii) sufficient injection altitude to enable the smoke to survive; (ii) uniform distribution of smoke in the latitude band 30° to 70°N, (iv) explicit neglect of any greenhouse effect which could counteract surface cooling (for example, by choosing a smoke particle size distribution yielding negligible infrared opacity). Their maximum surface temperature change is - 37°; time for half-recovery 76 days (assuming zero heat capacity for the surface but taking the heat capacity of the lowest 2 km of atmosphere) (NAS, Table 7.3). The NAS study with similar assumptions and using the TTAPS 1-D radiative model arrives at - 21°C; recovery in 51 days.

The use of 2-D and 3-D models, without changing the basic physical assumption, yields lower temperature excursions because of the moderating effect of oceans. For example, a Livermore study (MacCracken, 1983; see also NAS, p. 151) arrives at -11°C; recovery time 70 days. The NCAR study (Covey et al., 1984), again with TTAPS assumptions, plus some of their own, arrives at -26°C (in summer) and -17°C (in spring) NAS, p. 152).

If the physical assumptions are made more realistic, for example, if even a small greenhouse effect is considered, then the cooling effect is not only reduced but may turn into a warming ("nuclear summer"). Specifically (Table 1):

(1) A low altitude smoke cloud would make the surface temperature warmer by (308K-234 K) = 74 K than the TTAPS case.

(2) A high IR opacity of the cloud would make the surface temperature warmer by (278K – 234 K) = 44 K than the TTAPS case, even without any normal greenhouse effect.

(3) A cirrus cloud produced by the nuclear bursts could raise the surface temperature well above the ambient level of 303K – and far above the TTAPS levels - even if the cirrus albedo is 25%.

(4) A combination of any of the three effects would be additive and cause further warming of the surface.

9. New Results

9.1 Lifetime of Smoke

The lofting of smoke to altitudes above 5km appears to be possible only under special atmospheric conditions. As a rule, and especially in the presence of winds, smoke should remain below 5 km and be removed by rainout in a matter of days. An additional factor leading to lower altitudes and shorter lifetimes is smoldering, i.e., lower intensity but longer-lasting fires. [In fact, some 200 Tg of particulates are injected into the lower atmosphere annually without appreciable climate effects.] Smoldering also adds a heat input (Singer, 1984c) comparable to the reduced insolation assumed in the TTAPS study.

9.2 Greenhouse Effects

Contrary to the treatment by TTAPS, also followed by NAS, there are a number of separate, and additive, possibilities for greenhouse effects that reduce the heat loss from the surface, and may even lead to surface warming – a nuclear summer instead of a nuclear winter. They are:

a) Non-uniform (and therefore quite thick, IR-opaque) smoke clouds.

b) The normal greenhouse effect of the overlying ambient atmosphere, of importance when the smoke clouds are at low altitude.

c) A greatly enhanced greenhouse effect, effective even with high-altitude smoke clouds, due to radiative gases injected by the nuclear bursts. Especially effective should be stratospheric cirrus clouds created by the injected H_2O, and ozone near the tropopause created by NO_x in reactions with ambient and injected gases.

d) Intrinsic high IR opacity of the smoke cloud, created by the IR-active combustion gases and by a shift in the size distribution towards larger particles (by agglomeration, smoldering, chemical, and electric effects).

The ecological effects of a nuclear exchange can best be gauged from past climatological experience. Using the results on smoke lifetime and on greenhouse effect – and considering the moderating effects of the world's oceans – it seems unlikely that the climate effect involves much more than a temperature decrease of about 5°C lasting for a few days. Such climate events have occurred frequently in the last 100 years and have not produced special problems (Ken, 1985).

9.3 Ozone

Much has been made by TTAPS of the adverse ecological effects of an ozone decrease. The NAS report echoes this concern. Current knowledge suggests, however, that the NAS baseline case will lead to an ozone enhancement in the tropopause region and a decrease in the upper stratosphere, with a likely small net change in the vertical ozone column.

10. Epilog

The recognition of possible climate effects due to massive smoke injection from fires (Crutzen and Birks, 1982), whether initiated by a nuclear exchange or by other means, has stimulated atmospheric physicists, chemists and meteorologists, and opened new and useful areas of research – notwithstanding the unlikely occurrence of a nuclear winter.

Acknowledgments

I thank R. Brofft, R. Ehrlich, H. Ellsaesser, C. C. Kumar, and M. MacCracken for critical discussion. A special appreciation is owed to the late Dr. Helmut Landsberg; in December 1983, he chaired an ad-hoc group of atmospheric scientists who had assembled in Chicago in connection with an international conference on global environmental problems. The group discussed in some detail the physics underlying the just published "nuclear winter' phenomenon and identified issues for detailed investigation.

References

Aleksandrov, V. V., Stenchikov, G. L., 1983: Proc. Appl. Math., Computer Center of the Academy of Science U.S.S.R., Moscow

AMBIO 1982: Nuclear War: The Aftermath. *AMBIO*, **11**, 75-176

Bergstrom, R. W., 1973: Extinction and Absorption of Atmospheric Aerosol as a Function of Particle Size. *Contr. Atmosph. Phys.,* **46**, 223-234, quoted in NAS/NRC 1985

Cess, R. D. 1985: Nuclear War: Illustrative Effects of Smoke and Dust Upon Solar Radiation. *Climatic Change,* **7**, 237-251

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

Crutzen, P.J., Birks, J. W., 1982: The Atmosphere After Nuclear War: Twilight at Noon. *AMBIO*, **11** 114-125

Glasstone, S., Dolan, P.J., 1977: *The Effects of Nuclear Weapons.* 3rd edition, U.S. Dept. Defense, Washington DC

Greenberg, J. M., 1968 Interstellar Grains. In: B. M. Middlehurst and L. H. Aller (eds.), *Nebulae and Interstellar Matter*. University of Chicago Press, p. 249

Johnson, J. C., 1954: *Physical Meteorology*. New York: Wiley, 393 pp

Kearny, C. H., 1985: On a Nuclear Winter (letter). *Science,* **227**, 356-358

Kerr, R. A., 1985: Wild Strings of Winter Confirmed. *Science*, **227**, 506

MacCracken, M. C., 1983: Nuclear War: Preliminary Estimates of the Climatic Effects of a Nuclear Exchange. Quoted in NAS/NRC 1985

MacCracken, M. C., 1985, as quoted in J. E. Penner and L. C. Haselman, UCRL-92523 (preprint) Livermore, CA, April 1985. R. Ellington has developed a more elaborate 1-D model (preprint)

Malone, R. C., Auer, L. H., Glatzmeier, G. A., Wood, M. C., Toon, O. B., 1985: Influence of Solar Heating and Precipitation Scavenging on the Simulated Lifetime of Post-Nuclear War Smoke. *Science,* **230** 317-319

McNamara, R. S., 1977: Counterforce Strategy. In: J. E. Endicott and R. W. Stafford, Jr. (eds) *American Defense Policy*. Baltimore, MD: Johns Hopkins University Press

NASA/Dept. Transport 1984: Upper Atmosphere Programs Bulletin. Issue no. 84-1, Washington, DC

National Academy of Science/National Research Council (NAS/NRC), 1985: The Effects on the Atmosphere of a Major Nuclear Exchange. Washington, DC

Paltridge, G. W., Hunt, G. E., 1984: Three-dimensional Climate Models in Perspective. *AMBIO*, **13**, 387-388

Peczkis, J., 1988: Initial Uncertainties in "Nuclear Winter": A proposed test based on the Dresden firestorm. *Climatic Change* (to be published). Evidence for coagulation of smoke particles in forest fires is adduced by H. H. Watson, *Weather,* **7**, 128, 1952

Penner, J. E., Haselman, L. C., Edwards, L. L., 1985: Buoyant Plume Calculation. UCRL-909915 (preprint), Livermore, CA

Ramaswamy, V., Kiehl, J. T., 1985: Sensitivity of the Radioactive Forcing Due to Larege Loadings of Smoke and Dust Aerosols. *J. Geophy. Res.,* **90** 5597-5613

Singer, S. F., 1984a: Nuclear Winter and Nuclear Freeze, *Disarmament,* **7**, 63-72

Singer, S. F., 1984b: Is the Nuclear Winter Real? *Nature* **310**, 625

Singer, S. F., 1984c: The Big Chill? *Wall Street Journal*, 3 Feb. 1984

Singer, S. F., 1985: On a "Nuclear Winter" (letter). *Science*, **227**, 356

Small, R. D., Bush, B. W., 1985: Smoke Production From Multiple Nuclear Explosions in Non-urban Areas. *Science*, **229**, 465-469

Stothers, R. B., 1984: Mystery Cloud of AD 536. *Nature*, **307**, 344-345

Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B., Sagan, C. (TTAPS) 1983: Nuclear Winter : Global Consequences of Multiple Nuclear Explosions. *Science*, **222**, 1283-1292

Turco, R. P., et al. (TTAPS) 1985: On a Nuclear Winter (letter). *Science*, **227**, 358-362. They make a curious debating point (footnote 4), i.e., that 0.1 Mt bursts would effectively inject dust into the stratosphere; but they are contradicted by other authorities (Glasstone and Dolan, 1977; NAS/NRC, 1985)

Van de Hulst, H. C., 1980: *Multiple Light Scattering*. New York: Academic Press, vol. 2, 400-401

Author's address: Dr. S. Fred Singer, # 712 S, 1600 South Eads Street Arlington, VA 22002, U.S.A.