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ATMOSPHERIC CONDITIONS AFTER A NUCLEAR WAR

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Abstract

During a full scale nuclear war, the atmosphere would be loaded with huge quantities of pollutants, which are produced by fires in urban and industrial centers, cultivated lands, forests and grasslands. Especially detrimental are the meteorological effects of light absorbing airborne particles. Estimates are presented of the amounts of various types of fuels which would burn in the event of a major war and of the resulting particulate matter production. The fires could produce several hundred million tons of airborne particulate matter, by which the penetration of sunlight to the earth's surface would be reduced greatly over extended areas of the northern hemisphere, maybe even globally. This could temporarily reduce crop growth and biospheric productivity in important ways.

This situation would last for several weeks and cause very anomalous meteorological conditions. Much solar radiation would be absorbed in the atmosphere instead of at the earth's surface. The land areas and lower atmosphere would, therefore, cool and the overlying atmosphere warm, creating strong vertical thermal stability in a highly polluted atmosphere. For extended periods, worldwide weather patterns would be abnormal. The resulting cold, probably freezing, temperatures at the ground could also interfere severely with crop production during the growing season

and cause extreme conditions for large sections of the biosphere. The combination of lack of sunlight, cold temperatures and other abnormal meteorological conditions would add enormously to the already huge problems of the survivors.

1. Introduction

Many meteorological investigations have been devoted to the atmospheric transport and deposition of radioactive material from nuclear bomb testing. Very few studies have, however, been performed on the possible changes which may take place in the physics, chemistry and meteorology of the atmosphere as a consequence of a full scale nuclear war. Some early studies (e.g. Ayers, 1965; Batten, 1966) were too limited in scope and did not take into account the effects considered in this and an earlier study (Crutzen and Birks, 1982). The first major investigation which dealt with possible global, atmospheric and climatic effects of a nuclear war was conducted by a special committee appointed by the US National Academy of Sciences (NAS, 1975). Considerable attention was given to the global depletion of stratospheric ozone and the consequential, harmful biological effects of substantially increased penetration of ultraviolet radiation to the earth's surface. Earlier, Foley and Ruderman (1973), Johnston (1973), Johnston *et al.* (1973), and Hampson (1974) had proposed that the oxides of nitrogen (NO and NO_2), which are produced in the superheated air of the nuclear fireballs, would catalyze the destruction of ozone in the stratosphere by the set of reactions (Crutzen, 1970).

$$
\begin{aligned}
O_3 + h\nu &\rightarrow O + O_2 \quad (\lambda < 1140 \text{ nm}) \\
NO + O_3 &\rightarrow NO_2 + O_2 \\
NO_2 + O &\rightarrow NO + O_2 \\
\hline
\text{net:} \qquad 2\,O_3 &\rightarrow 3\,O_2
\end{aligned}
$$

As about 10^{32} molecules of NO are produced per MT of explosive energy (1 Mt = 1 megaton TNT = 10^{15} calories), a global war with detonations totalling 10^4 Mt would produce 50×10^{12} g NO. This is many times more than the amount which naturally resides in the stratosphere. Large reductions in stratospheric ozone by several tens of percent, lasting for several years, were calculated as a consequence of a major nuclear war in which large weapons with yields of more than 1 Mt would be detonated.

Such large weapons cause the hot fireballs to rise into the stratosphere (NAS, 1975). A several fold increase in the penetration of ultraviolet radiation to the earth's surface would result. This was considered to be the main, long-term, global, atmospheric effect of a total nuclear war. By cursory comparison with the reported effects of major volcanic explosions, the production of dust from nuclear ground bursts was estimated to lead to rather insignificant changes in the earth's climate.

Recently, Ambio, the environmental journal of the Royal Swedish Academy of Sciences, invited an international and interdisciplinary group of scientists to analyze again the environmental effects of nuclear war (Ambio, 1982). These studies were based on a targeting scenario, describing "how a nuclear war might be fought" (Barnaby *et al.*, 1982), which is also adopted for the present study and reproduced in Table I. It reflects probable US and Soviet strategic delivery capabilities in 1985. It does not describe the most probable war and may be more catastrophic than envisioned by many military experts. One third of all nuclear explosives would be directed

TAB. I - *AMBIO Scenario.*

A. Total number of warheads used: 14747
Total megatonnage used: 5742 Mt

Megatonnage used in Northern Hemisphere: 5569 Mt
Megatonnage used in Southern Hemisphere: 173 Mt

B.

Size of warheads	Number used
100 kt	939
200 kt	2930
300 kt	4410
500 kt	5692
1 Mt	769
10 Mt	7

C. Numbers of warheads used for different target categories, Megatons used for different target categories:

Military targets	6620 warheads	2960 Mt
Population (1124 cities)	4970 warheads	1941 Mt
Industry/Energy	3136 warheads	701 Mt
Closing of straits (14 straits)	21 warheads	140 Mt

D. Warheads used for different target categories:

Military	300 kt	(one 300-kt warhead per target)
	100 kt	(one 100-kt warhead per target)
	200 kt	(one 200-kt warhead per target)
ICBM		(two 500-kt warheads per silo)
Submarine Bases		(one 1-Mt warhead per base)
Population	1 Mt	(three 300-kt + one 100-kt per city)
	3 Mt	(three 1-Mt warheads per city)
	10 Mt	(ten 500-kt + five 1-Mt warheads per city)
Industry	1 Mt	(five 200-kt warheads per site)
Oil fields	1 Mt	(two 500-kt warheads per site)
Closing of straits	10 Mt	(seven 10-Mt + fourteen 500-kt warheads) (this is total for the 14 straits)

E. Military targets:

	Megatonnage per target (average)	
Air bases	300 kt	ground burst
Naval ports	300 kt	ground burst
Army bases	300 kt	ground burst
Command/control/radar	300 kt	ground burst
Early warning systems	100 kt	ground burst
SOSSUS	300 kt	water burst
ICBM	Two 500 kt warheads per silo	ground burst
Energy Resources targets:		
Hydro electric stations	10 kt	airburst
Other energy resources	10 kt	airburst
Oilfields	1 Mt	airburst
Industrial targets: (only large industrial complexes)		
Oil refineries	1 Mt	airburst
Chemical plants (heavy organics, urea/nitric acid. sulfuric acid, ammonia)	1 Mt	airburst
Cement	1 Mt	airburst
Iron ore/steel	1 Mt	airburst

against cities, which is totally senseless, considering the enormous death toll and the huge amount of injured survivors which it would cause (Middleton, 1982; Lewis, 1979). On the other hand, cities have been bombed extensively during the second world war, including two nuclear attacks. Furthermore, government centers, industries and military establishments are often located close to or in cities, so that city bombing seems inevitable during a nuclear war (Bracken and Shubik, 1982). The bombing of only

one major city would most likely provoke a massive retaliatory exchange involving many cities in the world. As long as there are so many weapons around, they may very well be used against cities, especially in a future world with the likelihood of nuclear proliferation. That the bombing of cities, or at least the fear of it, is included in military thinking follows clearly from the existence of elaborate evacuation plans in several countries (e.g. the USSR) and current proposals to institute them also in the U.S. The incredibility of limitation of a nuclear war in a complex military setting has been shown by Ball (1981).

For a variety of reasons, e.g. prevention of post-war superiority, the nuclear exchange would not only involve NATO and Warsaw Pact member states, but also Japan, China, India and Australia. Almost 45% (5740 Mt) of the available megatonnage worldwide (13000 Mt) would be used by the superpowers, delivered by 14750 warheads. The sizes of the warheads vary between 100 Kt and 10 Mt with an average of about 0.4 Mt. In this paper we will mainly explore the atmospheric effects of urban, industrial and forest fires, which would be started by nuclear explosions, neglecting the effects of conventional, non-nuclear weapons. We will also delete a discussion of the possible consequences of long-lasting fires in oil and especially gas fields, which could certainly be expected as a result of blowouts of production wells, but are difficult to quantify. The potential consequences of such blowouts could be very severe, as discussed by Crutzen and Birks (1982). The meteorological effects of soil-derived dust from nuclear ground bursts have likewise been disregarded in this study. Contrary to the statements of the NAS (1975), Turco *et al.* (1983) in a new study have indicated that they may not be neglected.

There is a very important difference between the nuclear arsenals which were adopted for the NAS (1975) and the AMBIO (1982) studies, reflecting rapid military developments. The NAS study assumed mainly the use of large bomb sizes, mostly with explosive yields of 1 Mt. For the Ambio Study, describing the likely strategic situation in 1985, Barnaby *et al.* (1982), on the other hand, developed a scenario with many more weapons of smaller sizes, much more in agreement with the currently available arsenals. The fireballs from these smaller bombs do not rise high into the stratosphere and much of the NO which is produced by them, will remain in the troposphere (Peterson, 1970). In this case a production of ozone is expected. This is due to reactions, again involving NO and NO_2 as catalysts (Crutzen, 1973), e.g.

$$
\begin{aligned}
CO + OH &\rightarrow H + CO_2 \\
H + O_2 + M &\rightarrow HO_2 + M \\
HO_2 + NO &\rightarrow OH + NO_2 \\
NO_2 + h\nu &\rightarrow NO + O \quad (\lambda < 400 \text{ nm}) \\
O + O_2 + M &\rightarrow O_3 + M \\
\hline
\text{net:} \quad CO + 2\,O_2 &\rightarrow CO_2 + O_3
\end{aligned}
$$

Similar, but more lengthy, reaction chains, leading to ozone formation, occur during the oxidation of hydrocarbons, with methane oxidation playing an important global role. The production of ozone would be further enhanced by the simultaneous production of NO_x, CO and various reactive hydrocarbons by the fires and by the gas and oil well blowouts, which would occur around the world. It was shown by Crutzen and Birks (1982) that this could lead to photochemical smog formation over large parts of the Northern Hemisphere. However, for such "photochemical smog" reactions to take place, the availability of sunlight is a prerequisite. As fires do also produce large amounts of black smoke which absorbs sunlight, an analysis of the aerosol production by the fires started during the nuclear war became necessary. This analysis led to the discovery of the most serious global, environmental consequence of a major nuclear war, discussed so far. It was shown that the presence of smoke could profoundly change global meteorological conditions.

In this paper a study of the effects of smoke evolution on atmospheric and environmental conditions will be presented. Much of the necessary information for such a study is quite uncertain, so that a very wide range of estimated effects is possible. The main uncertainties of the analysis are pointed out and "reasonable" choices are made, avoiding extreme assumptions. The main purpose of this paper is once again to show the enormous potential importance of the atmospheric and environmental effects and to provide background material for further studies.

2. Fires, particulate matter and their optical properties

During a nuclear war, many fires would start near urban, industrial and military targets (Barnaby *et al.*, 1982). We will try to make some rough estimates of the extent of fires in various categories of combustibles, the amount of particulate matter produced thereby, and its optical properties. We will use this information to estimate the effects of the particulates on

the penetration of sunlight through the atmosphere. A rather extensive survey of the fire research literature was made for this purpose. Data were gathered for the following categories of combustible materials: construction wood, oil and gas, synthetic polymers and forest fuels. For each of these the average, percentage yield of particulate matter and its graphitic or elemental carbon (EC) content were estimated. The mechanisms of soot or EC formation in flames have been reviewed by Wagner (1980) and Rasbash and Drysdale (1982).

The aerosol particles, which are important for this study, are combustion products and are initially mainly formed in the nucleation mode with radii much below 0.1 μm. Through coagulation, these embryonic particles recombine rapidly to larger sizes. The atmospheric lifetime of particles with radii less than 0.1 μm is, therefore, relatively short, under normal conditions less than a few days. Particles with radii larger than 3 μm are likewise removed rather rapidly from the atmosphere, mainly by gravitational settling. In the size range between ahout 0.1 μm and 3 μm, the so-called accumulation mode, atmospheric aerosol particles have the longest residence time in the atmosphere. This is mainly determined by precipitation scavenging and, as a global average, may range from about one week below 1.5 km, to one month in the upper troposphere, and about one year or longer in the stratosphere (Jaenicke, 1981).

There will, however, exist large variations in the removal rates of these aerosol particles, especially of the important elemental carbon component. In a recent study, Ogren and Charlson (1983) have presented an overview of the complex processes which determine the residence time of EC in the atmosphere. These authors distinguish between externally and internally mixed EC, the external mixture consisting of particles which have not yet combined with other types of occurring aerosol, i.e. rather "fresh" EC. Externally mixed accumulation mode EC particles are not expected to be efficiently incorporated in cloud droplets because they are hygrophobic and can, therefore, not act as cloud condensation nuclei. For such particles rainout and washout should be rather inefficient (Pruppacher and Klett, 1980, p. 395-396; Ogren and Charlson, 1983). With time, externally mixed EC is converted into internally mixed EC by coagulation with other types of aerosol particles or after the condensation of compounds from the gas phase, after which they may become hygroscopic and act as condensation nuclei. The residence time of EC in the atmosphere should, therefore, be longer than the average value

applying for aerosol. A more detailed discussion about these removal processes will be given in section 5 of this paper.

Airborne particulate matter scatters and may also absorb solar radiation. It is a remarkable coincidence of nature that the optically most effective aerosol particles are also the most long-lived ones. Tbese particles have a specific scattering of about 4 m^2/g aerosol, wbich is a typical value for various situations in the atmospheric environment, e.g. for forest fire smokes (Tangren, 1982; Radke *et al.*, 1978; Vines *et al.*, 1971) and urban and rural air (Waggoner *et al.*, 1981; Chylek *et al.*, 1981; Wolff *et al.*, 1979, 1981, 1982). The presence of graphitic or elemental carbon in aerosol is very important, as it leads to very efficient absorption of solar radiation. This material is only formed during flaming combustion. The specific absorption of "fresh", externally mixed, EC has been measured to range from about 5 to 20 m^2/g, with a mean value of about 10 m^2 per gram EC (Chylek *et al.*, 1981; Novakov, 1979, 1982; Cadle and Groblicki, 1982). Coagulation leads to the formation of larger aerosol particles, which, in the case of externally mixed EC, would absorb sunlight less efficiently (Chylek *et al.*, 1981). For aged aerosol, the specific absorption, as determined by observations in remote regions, seems generally to be equal to 10 m^2/g EC. This value will, therefore, be adopted in this study. A tbeoretical explanation for this has been given by Ackerman and Toon (1981). The specific scattering (b_s), absorption (b_a) and extinction (b_e) which will be adopted for an initial analysis are, therefore, given by

$$b_s = 4 \text{ m}^2/\text{gram aerosol}, \tag{1a}$$

$$b_a = r_{EC} \times 10 \text{ m}^2/\text{gram aerosol}, \tag{1b}$$

$$b_e = b_a + b_s \tag{1c}$$

where r_{EC} denotes the fraction of elemental carbon in the smoke particles. The radiative transfer calculation method followed in this study is only approximate. A more complete and self consistent analysis will be presented in a forthcoming paper (Crutzen *et al.*, 1984).

Information on particulate matter production in test fires has been compiled in Tables II-V. In a few instances, extinction cross sections were directly measured and used to derive the properties of the smoke particles. It is clear in all cases that available information is scanty, variable and uncertain. Because we are no experts in combustion research, we have checked our analysis with several combustion specialists and have gotten

TAB. II - *Literature survey on characteristics of aerosol produced by burning of wood.*

Ref. nr.	Type	Aerosol yield	Elemental C	m^2/g fuel (extinction)
1.	Fireplace, softwood Fireplace, hardwood	9 g / kg 10 g / kg	33% of aerosol 8% of aerosol	
2.	Residential wood		13% of aerosol	
3.	Laboratory test fires free burning ventilation controlled		50% soot	 0.023 0.15
4.	Laboratory test fires hardwood fibreboard	 0.085-0.16% 0.75%		
5.	Laboratory test fires	1-2.5% (flaming) 3.1-16.5% (non-flaming)		
6.	Laboratory test fires			0.01
7.	Laboratory test fires	0.2-0.6%		
"Average"		1%	20%	(0.06)

References: 1 (Muhlbaier Dasch, 1982), 2 (DeCesar and Cooper, 1983), 3 (Rasbash and Pratt, 1979, and personal communication D.J. Rasbash), 4 (Hilado and Machado, 1978), 5 (Bankston *et al.*, 1981), 6 (Tewarson, 1982), 7 (Seader and Einhorn, 1976).

the impression so far that our estimates are quite reasonable. More studies are, however, required.

Table II containing data on wood burning combines information from burning in fireplaces and from test fires of cellulosic materials, which are typically used in building construction. For this category of materials, we compromise to derive an average aerosol yield of 1% of the fuel burned, containing about 20% EC. References to the studies considered here have been listed in the Table captions. In the same way the information for the other categories of fires has been compiled in Tables III-V. In the derivation of the average quantities, we emphazised the importance of the flaming phase for the optical (light absorption) properties of the aerosol. Smoldering burning will produce larger particles, because of the greater probability of coagulation of embryonic particles from the slowly burning material (Mulholland and Ohlemiller, 1982). For the flaming burn-

TAB. III - *Literature survey on characteristics of aerosol produced in oil gas burning.*

Ref. nr.	Type	Elemental C	m^2/g fuel (extinction)
1.	Residual oil in burner	31% of aerosol carbon	
2.	Diesel engine	80% of aerosol	
	Gas furnace	90% of aerosol carbon	
3.	Light oil in burner	40-70% of aerosol	
	Natural gas furnace	40-70% of aerosol	
4.	Light oil in burner	40% of aerosol carbon	
5.	Oils, rubber	100% soot	0.7 - 1.2
6.	Oil slick	2-6% of fuel burned	
7.	Natural gas diffusion flames	all emissions as soot	3
	Heavy fuel oil » »	all emissions as soot	2
8.	Aliphatic oils	3-10% of fuel burned	
"Average"		5% of fuel burned	(0.7)

Note that references 1-4 all refer to clean burning in household equipment and are not representative for mass fires. References: 1 (Cooper and Watson, 1979), 2 (Muhlbaier Dasch and Williams, 1982), 3 (Nolan, 1979), 4 (Wolff *et al.*, 1981), 5 (Rasbash and Pratt, 1979; Rasbash, private communication), 6 (Day *et al.*, 1979), 7 (Maraval, 1972), 8 (Rubber and Plastics Research Association of Great Britain, letter to authors).

ing of plastics we derived rather similar, average properties as for oil and gas burning, so that these two categories will be combined (compare Tables III and IV). For each of the categories of combustibles, the average extinction coefficients have likewise been calculated from the derived information on aerosol yield and EC content, using formulae (1a)-(1c). The derived quantities have been printed within parentheses on the last lines of Tables III-V. We note that, compared to the measured values, the calculated extinctions are on the low side for fossil fuel and synthetic polymer and "in the middle" of the range for wood burning.

Large uncertainties also exist in the category vegetation and forest fires. The values compiled in Table V are lower than used by Crutzen and Birks (1982). Uncertainties mainly arise from difficulties in the sampling of forest fire plumes and the complex nature of forest fires in which different phases of burning (flaming and smoldering) occur simultaneously in a variety of combustible materials. This makes the interpretation of forest fire plume data very difficult. We consider some of the ship-

TAB. IV - *Literature survey on characteristics of aerosol produced by burning of plastics.*

Ref. nr.	Type	Aerosol	Elemental C	m^2/g fuel (extinction)
1.	Plastics		100% soot	0.2 - 1.6
	Rubber			1.0
2.	Various plastics	5-50% soot	2-40% of fuel	
3.	Polyethylene, styrene			
	PVC (flaming)	1.2-3.2%		
	Polyurethane (flaming)	9%		
4.	Plastics	6-20%		
5.	Plastics	3-5 %	100% soot	
6.	Plastics	11-20%	75% soot	
7.	Plastics			0.3 - 1.2
8.	Automobile components	5%		
9.	Plastics		60-100%	
10.	Polystyrene	3-10% soot		
11.	Polyethylene	5-8.3%		
	Polyisoprene	19.4%		
	Polystyrene	21.0%		
"Average"		5%	60%	(0.5)

References: 1 (Rasbash and Pratt, 1979, and D.J. Rasbash, personal communication), 2 (Morikawa, 1980), 3 (Bankston *et al.*, 1981), 4 (Hilado and Machado, 1978), 5 (J.E. Snell, personal communication), 6 (Tewarson *et al.*, 1981), 7 (Tewarson, 1982), 8 (EPA, 1978), 9 (Seader and Ou, 1977), 10 (Rubber Plastics Research Association of Great Britain, letter to authors).

board measurements by Andreae (1983) in the tropical Atlantic, which were clearly influenced by biomass burning effluents from the African and South American continents, to be of particular significance.

For all categories the exact determination of the elemental carbon content is a difficult physico-chemical problem. This may seem surprising as soot is so easily observable with the eye. The role of soot in atmospheric optics and climate is now attracting substantial attention (Novakov, 1979; Wolff and Klimish, 1982). Because of its radiative properties, deliberate weather modification with soot particles has been proposed and discussed (Gray *et al.*, 1976; Chen and Orville, 1977).

TAB. V - *Literature survey on characteristics of aerosol produced by vegetation fires.*

Ref. nr.	Type	Aerosol/fuel	Elemental C
1.	Slash burns		10 % of aerosol
2.	Vegetation burns		7.1% of all aerosol C
3.	Forest Fires		10 % of aerosol
4.	Prescribed forest fires	4%	
5.	Prescribed forest fires	2%	25 % "soot"
6.	High intensity forest fire, prescribed	0.44%	
	Low intensity forest fire, prescribed	2-4%	
7.	Agricultural burning		9 % of aerosol
8.	Forest wildfires		
	60% flaming	10 kg/ton	
	40% smoldering	60 kg/ton	
9.	Forest wildfires	70 kg/ton	
10.	Forest wildfires		4 % of aerosol
11.	Laboratory test fires		
	flaming		15 % of aerosol
	non-flaming		2.5% of aerosol
12.	Mid-Atlantic air samples		7 % of aerosol
13.	Slash burns		7-9% of aerosol
"Average"		4%	8%

References: 1 (DeCesar and Cooper, 1983), 2 (Cooper and Watson, 1979), 3 (Macias *et al.*, 1981), 4 (Radke *et al.*, 1978), 5 (Vines *et al.*, 1971), 6 (Evans *et al.*, 1977), 7 (Cass *et al.*, 1982), 8 (Wade, 1980), 9 (Ward *et al.*, 1976), 10 (Ouimette and Flagon, 1982), 11 (Patterson and McMahon, 1983), 12 (M.O. Andreae, 1983 and private communication), 13 (Shah, 1981).

Finally we note that the data which are compiled in Tables II-V are mostly based on simple laboratory tests with single specimen of typical fuel types. The applicability of these data to mass fires is debatable (Powell *et al.*, 1979). In fact, according to Rasbash and Drysdale (1982), the effect of the environments into which the fire volatiles are released is probably more important than the nature of the combustibles. Lack of ventilation enhances smoke production, as can clearly be seen from the data of Rasbash and Pratt (1979), listed in Table II. As shown in Tables II-IV, burning of unoxidized fossil fuels and plastics yields much more

smoke and soot than the burning of half oxidized wood (Rasbash and Drysdale, 1982). It is also instructive to note that per gram of fuel, forest fires produce about 4 times more aerosol than the burning of wood in fireplaces and laboratory tests, which might be the result of more limited supply of oxygen in forest fires. For this reason, the acceptance of the derived average aerosol optical properties of Tables II-IV for the remainder of this study may well imply a considerable underestimation of the aerosol and soot production and of the absorption and extinction of sunlight in the atmosphere by mass fires.

3. Quantities of various materials burned

3.1 *Forest fires*

Temperate and and boreal forests occupy a total area of 24×10^6 km^2. Crutzen and Birks (1982) guessed that forest fires following a nuclear war might destroy a total area of 10^6 km^2. This is 55 times larger than the area which is annually subjected to wildfires in the US (excluding Alaska). For the temperate and boreal forests the area which is annually affected by wild-fires is 5-10% of one million km^2. The available statistics of the US Forest Service (Ward *et al.*, 1976) give a forest wildfire area of 0.18 million km^2 in the 1930's in the US, about ten times higher than at present. This reduction is of course due to the effective fire fighting and prevention programs which were instituted in the US since the 30's.

For the Ambio Scenario it may be calculated that about 22% of the nuclear explosions would occur in forested regions (Galbally *et al.*, 1983). With maybe millions of ignitions starting simultaneously over large areas effective fire fighting would be clearly impossible following a nuclear war. Especially during the summer season in large tracts of woodlands the probability of fire spread is substantial. During August probabilities are larger than 50% for the occurrence of "actionable" or "critical" fire spread conditions in the Western half of the US (Schroeder and Chandler, 1966). Under "actionable" conditions fires would still spread, if not fought; under "critical conditions" effective fire fighting is impossible. In a related study Huschke (1966) estimated that for half of the time, as much as 50% of all US timber lands are medium or highly flammable during the summer months.

Only a few estimates have been made of the forest fire spread from nuclear detonations. Hill (1961) quotes from earlier US Forest Service studies (not available to the author) minimum forest fire areas of 500, 1000, and 2100 km^2 for 1, 3 and 10 Mt, respectively. These areas correspond to fire occurrence at all points where the radiant heat pulse from nuclear detonations exceeds 15 cal/cm^2. Maximum spread areas which are listed by Hill (1961) are at least a factor of ten higher.

The deductions of forest fire spreads are extremely difficult and uncertain, depending critically on meteorological conditions and therefore seasonally dependent. It is not straightforward to extrapolate the above fire spread areas for the Ambio scenario, as in some areas there will be dense targeting and considerable overlap between potential fire areas. In an earlier study a forest fire area of 10^6 km^2 (Crutzen and Birks, 1982) was assumed. This estimate has been attacked both for being much too small and much too high by various forest experts. All recognize the seasonal dependence of the estimate and one forest expert even suggested that 5-10 million km^2 of forest might burn in Alaska and Siberia during the summer. A thorough, global analysis is necessary. This should also include estimations of long-lasting fires, as much forest area would be destroyed by radioactivity (Woodwell, 1982) and by post-war climatic changes. For this study we will assume a total forest fire area of 10^6 km^2, but will also give results for a case in which forest fires are neglected.

With an area of 10^6 km^2 and average biomass density of 20 kg/m^2, 4×10^{15} gram of biomass would burn as a consequence of a nuclear war. This assumes that 20% of all available fuel in the forest fire area, mostly leaves, duff, small twigs, branches and bark would burn, which is a reasonable estimate for normal forest fires. It may be an underestimate for any wild fires started by nuclear explosions, as blast effects will break larger size materials and pile much of it up on the forest floor. Furthermore, in this study no account was taken of the aerosol production by fires which might take place in organic forest soils or peat bogs (Shostakovitch, 1925), and other plant communities than forests, such as brushlands and agricultural lands.

3.2 *Urban and industrial fires*

The estimation of the areas which would be destroyed by urban and industrial fires is likewise a difficult task, as the results would vary from city to city. In order to reach some quantitative estimates, we prefer

to extrapolate here from the nuclear fire experiences of Nagasaki and Hiroshima. For Nagasaki the completely burned-out area covered 7 km^2 due to a 22 Kt weapon. At Hiroshima a 12 Kt weapon caused the burnout of 13 km^2 (Hill, 1961; Ambio, 1982). This can be translated in a total burnout for radiant heat pulses larger than 20 cal/cm^2 in Nagasaki and 7 cal/cm^2 in Hiroshima in the initial flash (Hill, 1961; Glasstone and Dolan, 1977). The difference in these threshold values is due to a combination of topographic and constructional factors. Parts of Nagasaki were protected from ignitions by high hills, while the building density in Nagasaki was appreciably lower than in Hiroshima (Ishikawa and Swain, 1981). At a radiant pulse of 20 cal/cm^2 even heavy fabric, such as draperies and furnishings, will catch fire. Thinner fuels such as dried leaves and newspapers will ignite at about 5 cal/cm^2. Between 5 and 20 cal/cm^2 potential fuels such as books, industrial trash and Kraft corrugated board will ignite (Martin and Broido, 1963).

Adopting a conservative criterion of 20 cal/cm^2 for burnout, the average nuclear weapon of 400 Kt, as adopted in the Ambio scenario, would destroy an area of about 150 km^2 by fires. We may note that this area of destruction is about a hundred times larger than that covered by the initial fireball. With a total use of 1940 Mt of nuclear explosives against cities, the total burned area over the entire earth would be almost 0.8 million km^2. This estimate does not take into account that industrial and military targeting, which was counted as a separate category in the Ambio study, would likewise start fires in many urban areas. It also neglects firespread, which may be substantial, as the experience in Hiroshima showed.

We may compare this estimate of global burnout with that which may be derived from information in the OTA (1979) study. According to this study for a 1 Mt burst on Detroit, the main fire area would cover 180 km^2. For the Ambio scenario this would extrapolate to 0.35 million km^2.

For the following discussion we use an average of 0.5 million km^2 for the total urban area, which would be attacked by fires. This is about 30% of the combined area of all cities in the world with more than 100,000 inhabitants. An area of this size is ten to forty thousand times larger than that burned during the Hamburg firestorm of July, 27-28, 1943 (Ebert, 1963; Caidin, 1960).

Data on fuel load densities in urban areas are scarce. In German compilations the following typical values for fuel loads per m^2 of floor

area are given: 40 kg for offices, 125 kg for libraries, 50 kg for laboratories, 60 kg for chemical factories and a wide range 12-120 kg for various other uses. Compilations for the US (FEMA, 1982; Culver, 1976) give values of 50-100 kg/m^2 for residential buildings, 50-200 kg/m^2 for offices, up to 150 kg/m^2 for industries and 100-400 kg/m^2 for storage spaces. Floor area fire loads for apartment buildings seem to be of the order of 25 kg/m^2 in the U.K. (Rasbash, 1967) and 50 kg/m^2 in Japan (Morikawa, private communication). Furniture mass loadings in homes in the UK may range from 10-14 kg/m^2 in bedrooms to 14-22 kg/m^2 floor space in sitting rooms (Rubber and Plastics Research Association of Great Britain, letter to the authors). For pre-second world war city appartments in Germany an average fire load density of 110 kg/m^2 floor area may apply. In modern buildings this may be 40 kg/m^2 (Schmitt, 1954). The fire loads in high-rise buildings may be larger than 1000 kg/m^2 as an analysis for office buildings in the U.S. has shown (Culver, 1976).

The fire loads per unit ground area in cities are of course very variable. For a modern German city center a reported value is 130 kg/m^2; in an older city 330 kg/m^2 may be more appropriate (Schmitt, 1954). The fire load in the Hammerbrook section of Hamburg prior to the firestorm of July, 1943, was 300 kg/m^2 (Ebert, 1963). In the central parts of some older cities fire load densities may, therefore, be very high. In their evaluation of the potential behavior of large urban fires for three model American cities, Larson and Small (1982) adopted total areal fire loads of almost 240-640 kg/m^2 for the city centers out to 1-2 km radius, 70-190 kg/m^2 for the inner belt out to 3-6 km and 18-50 kg/m^2 for the outer belt out to 12 km. Their analysis leads to overall areal fire load densities of 270, 45 and 23 kg/m^2 for cities in the Eastern, Middle and Western US, respectively. Considering the overall population distribution, the higher values are more representative for the case of an all-out nuclear war. The effects of blast on fire behavior must also be considered, but is unknown (Wiersma and Martin, 1973). This may lead to extinction or enhancement of fires. For this reason, Larson and Small (1982) performed two sets of model calculations. For one set it was assumed that all material in the cities would burn; in the alternative case it was assumed that blast effects would bury most combustible material in the inner parts of the city so well that little of it would burn. The latter possibility seems doubtful, at least for US cities, when we consider that only 25 years ago the cities of Washington and San Francisco contained as much as 96-99% combustible construction (Broido, 1960).

For the present calculations we will adopt a value of 40 kg/m^2 for the fire load density in urban areas. This may not be too far off from a reasonable value if city centers would be preferentially targeted and blast limited most of the fires in the central parts. However, it could be an underestimate, if this is not the case. We will also assume that only half of the buildings or half of the available fire load of 40 kg/m^2 would actually burn, i.e. 20 kg/m^2 (OTA, 1979). Altogether, in the urban area of 0.5 million km^2 at least 10^{16} gram of fuel would be consumed by fires. Most of this material will be wood in constructions and furniture, but it will also contain an appreciable fraction of synthetic organic polymers (plastics), which produce aerosol and soot much more efficiently than wood.

For the purpose of the present study, we assume the aerosol produced by the burning of plastics to have similar properties to those produced from oil and gas fires. These materials are all stored in large quantities in urban areas. The annual world-wide production of synthetic organics is about 6×10^{13} g (U.N., 1981). According to Marland and Rotty (1983) about 2×10^{14} g or 4% of the global fossil fuel production is not immediately burned, but converted to various longlived materials. About half of this material is asphalt. Polymeric materials are becoming increasingly common and may constitute as much as 10-20% of all combustible materials in German buildings (Verband der Sachversicherer e.V., personal communication). This percentage will probably increase substantially in the future (Anonymous, 1975). Lacking a more thorough analysis, we guess that about 10^{15} g of polymeric synthetic materials have accumulated worldwide. This is based on an average lifetime of about 20 years.

The global fossil fuel storage is about equivalent to 3-5 months of consumption. To this must be added the energy stored for domestic heating and for industry, and in military stock-piles. The total may amount to 2×10^{15} g. Large amounts of asphalt have accumulated in cities and part of this will also burn vigorously, as e.g. during the Hamburg firestorm (Caidin, 1960). As this material is longlived, the amount of asphalt which may have accumulated globally may be about 3×10^{15} g.

Altogether, a total of about 6×10^{15} g of synthetic polymers, fossil fuels and asphalt may have accumulated worldwide. Especially, as oil storage facilities and refineries are likely targets, it seems reasonable to assume that 10^{15} g of material in these categories would burn.

We repeat that in this paper we have not considered the consequences of the fires which could start in coal dumps or due to blowouts in oil and

gas production wells, because these are difficult to quantify. The latter is, however, a serious possibility, as testified by several military documents (Marriott, 1974/1975; Judd, 1975; Wall, 1976/1977; Simpson, 1976).

4. Darkness production potential of the Ambio scenario

The information on the quantities of combusted materials, and on aerosol and elemental carbon production, which is collected in Tables II-V, has been combined in Table VI to derive the state of the atmosphere during the nuclear war. We assume that the war would last for only a few days; the aerosol particles would also be given off to the atmosphere in such a short time. Most fire produced aerosol would initially be located between 30°N and 60°N, where most of the nuclear targets are located. If the nuclear explosions would occur over a period of three days, the fire plumes produced on the West and East coast of the US and over Europe (including the USSR) could cover most of the 30-60°N latitude belt, except the Pacific Ocean. This is based on an average westerly wind speed of 20 m/s in the middle and upper troposphere (Oort and Rasmussen, 1971). Spread in South-North direction within the latitude zone should

Tab. VI - *Compilation of optical depths over* 60% *of the* 30-60°N *latitude bel* (6×10^{13} m^2), *immediately following a nuclear war according to the Ambi scenario. The quantities* d_s, d_a *and* d_{ext} *are the estimated average optica depths for scattering, absorption and total extinction, respectively, calculate for overhead sun conditions. Quantities within parantheses neglect smok production by forest fires.*

Category	Fuel (burned (g)	Aerosol produced (g)	Elemental Carbon produced (g)	d_s	d_a	d_{ext}
Cities/Industries						
Wood	1.0×10^{16}	1.0×10^{14}	2.0×10^{13}	6.6	2.0	8.6
Oil, asphalt, polymers	1.0×10^{15}	0.5×10^{14}	3.5×10^{13}	3.3	5.9	9.2
Forest fires (10^6 km^2)	4.0×10^{15}	1.6×10^{14}	1.3×10^{13}	10.7	2.2	12.9
Total	1.5×10^{16}	3.1×10^{14}	6.8×10^{13}	20.6 (9.9)	10.1 (7.9)	30.7 (17.8)

occur very rapidly, because altogether about 15,000 nuclear detonations would occur. The area which would be initially covered by smoke would, therefore, be equal to 6×10^{13} m^2.

The average optical depth for this aerosol-covered part of the earth can for each category of combustibles be calculated from the formulae

$$d_s = F \times b_s / 6 \times 10^{13} \quad (2a)$$

$$d_a = F \times b_a / 6 \times 10^{13} \quad (2b)$$

$$d_{ext} = d_s + d_a \quad (2c)$$

where b_a and b_s are defined by equations 1a and 1b, and F is the quantity of aerosol produced. The symbols d_s, d_a and d_{ext} are the optical depths for scattering, absorption and total extinction, respectively. These are shown for each of the categories of fires in Table VI. The sums of these quantities are so large that, for a few days, very little sunlight could reach the smoke covered part of the earth. In section 6 we estimate that the transmission of sunlight to the earth's surface might be less than 10^{-5} for several days. These conditions are caused by the production of 2-3 $\times 10^{14}$ g of aerosol, of which about 6×10^{13} g would consist of elemental carbon.

Darkening of the sky and large reductions in the total amounts of sunlight reaching the surface over extended areas have been documented for large forest fires. Descriptions of such observations can be found in Crutzen and Birks (1982). Effects of forest fires in Western Canada in 1950 were clearly observable in Europe (Smith, 1950; Wexler, 1950). If we extrapolate these relatively small events to the huge extent of burning in the case of a nuclear war, the afore described enormous effects become entirely plausible.

It may be noted that this large quantity of aerosol is produced by the burning of one million km^2 which covers only one percent of the surface of the continents. Much of the material produced during the most intense periods of fires would be deposited at high levels in the troposphere (and maybe lower stratosphere). During the Hamburg firestorm the smoke columns may have reached 13 km (Caidin, 1960; Ebert, 1963). The high rising effluents contain most of the light absorbing aerosol. The particulate matter, which is formed by smoldering burning and which does not contain elemental carbon, will remain much closer to the ground. This aerosol would substantially reduce visibility and could, together with the many other air pollutants, cause bad health problems for many of the survivors of the war.

We emphasize that the described situation would be appropriate only for the first few days during or following the nuclear war. In the following section we will analyse how later the aerosol might influence other parts of the earth. The effects of rainout will be taken into account.

5. Precipitation scavenging

We have noted that the lifetime of airborne particulate matter between 0.1 μm and 3 μm is mainly determined by precipitation scavenging, leading to average residence times of about one week in the lower and one month or longer in the upper troposphere and stratosphere. This range of values will be used in the following analysis. Here we will first discuss the possible loss of aerosol in the convection clouds which may be stimulated by the fires. Scavenging taking place in the rising convective coluunn of the superheated air of the fireball will not be considered. This is justified by the fact that the initial area of the fireball is only about one percent of the total fire area.

Precipitation efficiencies (precipitation/condensation) of naturally occurring convective clouds are quite variable, but may average about 50% (Slinn, 1982). Removal of aerosol may, however, be more efficient (Hobbs and Molenkamp, personal communications). Nothing is known about the rainout efficiencies of the "fumulus" clouds which are stimulated by the buoyancy of the fires. However, not all fires will cause such convective cloud formation.

The following arguments may indicate that precipitation scavenging of fresh EC in "fumulus" clouds may not be too important.

a) Following Galbally *et al.* (1983) we may roughly estimate the volume of the plume of a city fire by assuming a width of 5 km, a typical duration of the fire of 12 hours and a mean zonal wind velocity of 20 m/s. For an assumed vertical injection column of 7.5 km, the fire plume volume would be 3×10^{13} m^3. For the 15,000 fires as envisaged in the Ambio scenario, the volume of air initially filled with smoke may thus be of the order of 4.5×10^{17} m^3, containing about 2×10^{17} kg of air. The heated air rising up from the lower troposphere into the plume might at most have contained about 10^{18} g of water vapor, if entrainment is neglected. This is the amount of water which at most can rain out in the fire induced convective storms. The 10^{16} g of water vapor which are created by the burning of the combustibles are negligible compared to this.

b) Eagan *et al.* (1974) observed a production of 6×10^{10} cloud condensation nuclei (CCN) per gram of forest fuel consumed. This can only represent a few percent of all fire generated aerosol. Most of this aerosol, in which we are particularly interested, is produced with mean radii less than 0.1 μm (Ward *et al.*, 1976), so that 6×10^{10} CCN in this size range would represent a mass of 2×10^{-4} g. One gram of forest fuel produces, however, a much larger total of $2\text{-}7 \times 10^{-2}$ g of particulates (Ward *et al.*, 1976). On the average about 22% of the aerosol produced during the flaming combustion of various combustibles consists of EC (see Table VI). For forest fuels the EC content is 8%. It can not be expected that EC would be preferentially used as CCN, as fresh soot particles are hydrophobic (Ogren and Charlson, 1983), and in any case the CCN could only be a minor fraction of all EC produced by the fires.

c) The global mass fires would consume 10^{16} g of combustibles, mostly wood, so that $N_a = 6 \times 10^{26}$ cloud condensation nuclei would be created by the fires. If all of these were activated, the average droplet size r_a may be determined from the equation

$$N_a \times 4/3\,\pi\, r_a^3\, \rho_a = G$$

where $\rho_a = 1$ g/cm^3, $N_a = 6 \times 10^{26}$ and $G = 10^{18}$ g water.
It follows that $r_a = 7.5$ μm for an average droplet concentration of $n_a = 1000$/cm^3. The average separation between droplets would be 800 μm. In comparison Eagan *et al.* (1974) measured $r_a = 4$ μm and $n_a = 3700$ cm^{-3} in the plume of a forest fire. Under these conditions, the time needed for precipitation to form by collision and coalescence will be prohibitively long. As the average fall velocity of a droplet of 7.5 μm radius is 0.2 cm/s, it follows that in one hour such a droplet can only grow to at most two times its original size by collision and coalescence. A typical microscale turbulence length is about 1000 μm, compared to an average droplet radius of 7.5 μm, making turbulent shear and inertial coagulation very inefficient processes (Pruppacher and Klett, 1980, pp. 373-375 and 506-507).

d) It follows from the above discussion that efficient precipitation can develop in the "fumulus" clouds only if a small fraction of the cloud condensation nuclei will be activated. However, in this case the scavenging efficiency for the fire generated aerosol particles in the size range 0.05 – 1 μm (the "Greenfield gap") is negligible (Pruppacher and Klett, 1980,

pp. 395-396). The low efficiency of aerosol scavenging in the "Greenfield gap" has, however, been questioned following observations on aerosol scavenging by precipitation falling through plumes from coal power plants and a Kraft paper mill (Radke *et al.*, 1980; Slinn, 1982). These measurements and their interpretation are still debated. As a possible explanation for the observations it was proposed by Radke *et al.* (1980) that the particles became dry when measured, while in the atmosphere they had deliquesced into larger particles. This nucleation scavenging mechanism may be very important for hygroscopic aerosol, including aged, internally mixed soot particles, which have become hygroscopic by absorption of suitable compounds from the gas phase or coalescence with more hygroscopic aerosol. For fresh soot particles, which are hydrophobic, the "Greenfield gap" may well be intact (e.g. Covert and Heintzenberg, 1983). Although it has long been known that "black rains" may accompany large forest fires (Plummer, 1912) and these were also reported in connection with major city bombings (e.g. Hamburg, Caidin, 1960; Nagasaki and Hiroshima, Ishikawa and Swain, 1981), the effectiveness of aerosol removal by rain is difficult to quantify. "Black" rains may also be due to downdraft effects and washout or rainout of large, partly burnt aerosol particles which rapidly coagulate with raindrops. About 20% of the aerosol produced by forest fires is found in the 1-5 μm size range and 10% is larger than 5 μm (Ward *et al.*, 1976), so that substantial production of supermicron particles may be expected for all fires. For very intense, large forest fires, it is clear from world-wide reports that that precipitation scavenging can not cleanse the atmosphere efficiently enough to prevent major obscurations of the sun over transcontinental distances (Plummer, 1912; Shostakowitch, 1925; Wexler, 1950).

The observations by Radke *et al.* (1982) of efficient removal of aerosol particles produced by the TITAN satellite launch (P.V. Hobbs, personal communication) may not be applicable, as the aerosol from the TITAN launch must have been strongly hygroscopic because of the presence of high concentrations of the combustion product HCl, which with ambient NH_3 will produce yield NH_4Cl aerosol.

Based on the previous arguments, we will neglect the prompt removal of aerosol in "fumulus" clouds, but recognize that the validity of this assumption is based on a very simple, mostly theoretical, analysis of the very complex phenomenon of mass fires, about which there exists very little observational information. Although more information can be gained by observations of major forest wildfires, even these do not simulate the

special features of fires in urban and industrial centers in which enormous amounts of combustibles are set on fire simultaneously over a large area and in which the fireball rise may induce huge and complex convective circulation systems, which may reach into the stratosphere. Therefore, despite the arguments presented in favor of only a relatively small removal efficiency of the soot particles by "fumulus" clouds, there remains the feeling of a possible lack of essential information on this issue. In the following we will note that precipitation scavenging is also the most critical factor determining the residence time of aerosol in the atmosphere and that knowledge about this is quite uncertain.

6. Atmospheric dispersion, rainout and sunlight transmission

We have roughly estimated that the 2-3 $\times$ 10^{14} g of particulate matter would initially cover an area of 6 $\times$ 10^{13} m^2 and occupy a volume of 4.5 $\times$ 10^{17} m^3. This implies an average particulate concentration of 4.4-6.7 $\times$ 10^{-4} g/m^3 in the early smoke clouds. Following the initial phase, the aerosol particles will spread out over larger areas, and be gradually removed by rainfall.

For the treatment of spread and rainout of the particles we must in this study assume similar behavior as during normal atmospheric conditions. Tbis is probably not valid, as much sunlight absorption would take place in the atmosphere and not at rhe earth's surface. This would lead to profound and global changes in many meteorological processes. For this study, however, it is impossible to treat these problems satisfactorily and we must rely on a simple model, based on current experience.

The average residence times against rainout and washout for 0.1 $-$ 3 μm size particles range from about 10 days in the lower to 30 days in the upper troposphere and to more than one year in the stratosphere (Jaenicke, 1981). There will of course be substantial variations in the rainout removal rates, which may vary from 3 days in rainy to much more than one week in dry climatic regions (Ogren and Charlson, 1983). These variations can not be treated with the simple model which is at our disposal. We will, therefore, perform calculations for the first month following the war, assuming various characteristics scavenging times (t_r) of 10 and 30 days, and also negligible rainout. The latter applies to that fraction of the aerosol which would reach the stratosphere. We will indicate later that there is a real

possibility that this may occur to the differential heating of the smoke clouds.

The horizontal spread over area A (t) of the aerosol clouds with time (t), expressed in m^2, can be roughly described by the formula

$$(3) \quad A(t) = 6 \times 10^{13} + 4 \times 10^{13} \left[1 - \exp(-t/t_a)\right] + 6 \times 10^{10} \sqrt{t}$$

The terms on the right hand side describe the area of initial coverage, and the spreads in East-West, and in South-North directions, respectively. The parameter t_a is chosen to be 10 days and corresponds to the time which is needed to fill the gap in the aerosol cloud cover which would initially be located over the Pacific. Given an average zonal wind shear of about 10 m/s between lower and upper troposphere (Oort and Rasmussen, 1971), the gap of 6000 km may be filled in about a week. The North-South spread of the cloud outside the 30-60°N latitude belt is simulated by a horizontal eddy diffusion model with an average exchange coefficient K_{yy} of 10^6 m^2/s (Hidalgo and Crutzen, 1977). Figure 1 gives the percentage coverage of the earth by the smoke layers, as calculated with formula (3).

Although coagulation of aerosol particles affects the transfer of

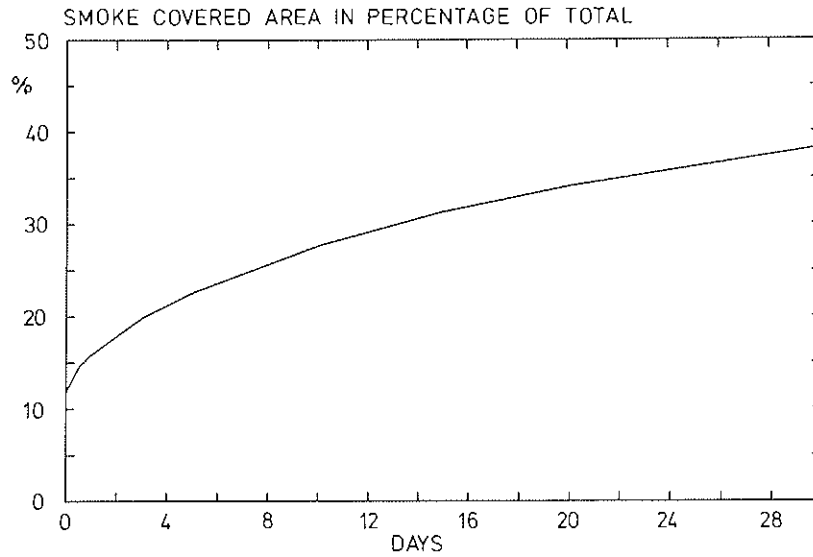

FIG. 1. Estimated percentage coverage of the earth's surface by smoke clouds as a function of time (in days).

radiation through the smoke clouds, observations in remote areas have generally established a specific absorption of 10 m^2/g EC for aged, internally-mixed elemental carbon. For this reason, the following, approximate formulae for the optical depths for scattering and absorption at time t may be used:

$$d_s(t) = d_s(o) \frac{A(o)}{A(t)} \exp(-t/t_r) \tag{4a}$$

$$d_a(t) = d_a(o) \frac{A(o)}{A(t)} \exp(-t/t_r) \tag{4b}$$

$$d_e(t) = d_s(t) + d_a(t) \tag{4c}$$

In these formulae, t_r denotes the average, characteristic rainout time of the aerosol particles, while the initial depths are given in Table VI.

An approximate method to calculate transmission of sunlight through the atmosphere via an effective optical depth of the atmosphere taking into account both scattering and absorption has been derived by Sagan and Pollack (1967). Although their method is mainly valid for large optical depths, we will use it also in this study. For small optical depths an upper limit for the average transmission of sunlight to the earth surface could be derived by the formula:

$$T = \exp(-2\, d_a). \tag{5}$$

The appearance of the factor 2 in this formula simulates the globally averaged zenith angle of the sun.

Sagan and Pollack (1967) derived an effective optical depth (d_{eff}) with the following formulae:

$$d_{eff} = \sqrt{3}\, u (1 - \omega_o)\, d_e, \tag{6}$$

whereby ω_o (the single scattering albedo) and u are given by

$$\omega_o = \frac{d_s}{d_s + d_a} \tag{7}$$

$$u^2 = \frac{1 - \omega_o + 2\beta\omega_o}{1 - \omega_o} \tag{8}$$

The parameter β is a measure of the fraction of radiation which is scattered backwards. For the present calculations β may be set equal to 0.15 (Twomey, 1977, p. 226).

The transmission, reflection and absorption of the solar radiation may finally be calculated by the formulae:

$$T = \frac{4\,u}{(u+1)^2 \exp(d_{eff}) - (u-1)^2 \exp(-d_{eff})} \tag{9}$$

$$R = \frac{(u+1)(u-1)\,[\exp(d_{eff}) - \exp(-d_{eff})]}{(u+1)^2 \exp(d_{eff}) - (u-1)^2 \exp(-d_{eff})} \tag{10}$$

$$A = 1 - T - R \tag{11}$$

The calculated transmissions of solar radiation to the ground are shown in Figure 2 for the cases $t_r = 10$ days, 30 days and no rainout at all. When

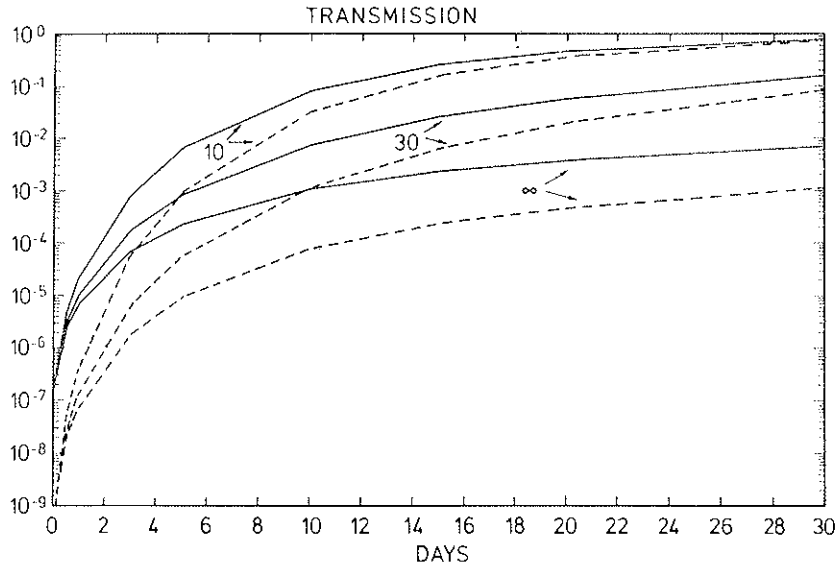

FIG. 2. Calculated transmissions of sunlight to the earth's surface under the smoke clouds for three characteristic rainout removal times of the smoke (10, 30, ∞ days). The dashed curves take into account the burning of one million km² of forests; the full lines neglect forest fires.

the effects of the burning of 1 million km^2 of forests are considered, we note that even for the relatively fast rainout case with $t_r = 10$ days, the penetration of radiation to the earth's surface remains below 1% of normal for about 7 days and below 10% for 12 days. The transmission calculated for day 30 is in this case still only about 70%. With a rainout time equal to 30 days, light levels would remain below 1% for 14 days and below 10% for 30 days. On day 30, the transmission of sunlight is only 10% of normal. By this time, the aerosol layer would cover about 70% of the northern hemisphere. With no rainout at all, the transmission of sunlight would remain below 0.2% for an entire month. It is clear that these results may describe only average conditions. In reality the smoke cloud cover could be rather patchy, randomly causing the appearance of dark and more normal daylight conditions. Figure 2 also contains the calculated transmissions, if forest fires are neglected. In this case the effective optical depth is reduced by about 30%. Large reductions in sunlight transmissions remain.

The results of the calculations are clearly very sensitive to the adopted rainout scavenging rates and this is probably the most uncertain aspect of our analysis. Conditions could become especially severe, and spread rapidly over the globe if a substantial fraction of the aerosol would reach the stratosphere, or if changes in the static stability of the atmosphere or physical properties of the clouds would prolong the average residence times of aerosol particles to much longer than normal. It may be argued that this might indeed occur. For instance, the atmospheric heating rate in the upper sunlit parts of the smoke layers during the first days of their existence may be calculated from the elemental carbon concentration of 1.5×10^{-4} g/m^3 and a mass absorption cross section of elemental carbon of 10 m^2/g to be as high as 50 K per hour. This would strongly favor the rapid upward convection of smoke, probably into the stratosphere (Galbally *et al.*, 1983; Crutzen and Birks, 1982). Furthermore, the higher air temperatures which would result, hinder condensation processes and promote cloud evaporation.

In fact, it is quite possible that the initial fireballs of low-altitude nuclear bursts could drag large amounts of vaporized carbon (and other oxidizable materials, such as aluminium) into the upper atmosphere. We have not included this process in our numerical calculations but, because of its potential importance, we provide a few comments on its nature here. We have seen that fire loadings in the inner parts of cities may be several hundred kilogram per square meter. If much of these combustibles would

vaporize within the fireball (see Glasstone and Dolan, 1977; Gilmore, 1974), for a 0.4 Mt explosion, the ratio between the moles of carbon and atmospheric oxygen could be in the range of 10-100. After stabilization of the cloud near the tropopause between 7 and 13 km, the nuclear cloud radius would be about 5 km. Entrainment would have decreased the C/O_2 ratio to 5×10^{-3}. However, oxidation of elemental carbon effectively stops at 1500 K. The C to O_2 ratio at that instant would be several percent and inhomogeneities in the composition of the clouds may lead to incomplete oxidation, EC formation and its deposition in the upper troposphere or lower stratosphere. As of the order of 10^{15} g of combustible materials could be confined in fireballs, the production of EC by this means and its direct deposition in the upper atmosphere could be very important.

7. Biological and meteorological consequences

For different rainout rates we have calculated widely different transmission of solar radiation through the atmosphere. For slow rainout rates, the transmission may remain below 10% for a whole month (see Figure 2), which means that sunlight transmission would be less than 1%, if twice the amount of aerosol were to be dumped in the atmosphere. Because of the uncertain analysis of the amounts of fuels burnt and particulate matter formed from different materials, and considering also the simplicity of the model adopted in this study, this possibility may not be discounted. A prolonged stay of aerosol particles in the atmosphere would occur if much particulate matter rapidly reached the stratosphere because of the intense solar heating of the smoke clouds.

A reduction in sunlight to much below one percent could create severe biospheric conditions. Phytoplankton and herbivorous zooplankton in the oceans could die, if conditions of at most one percent sunlight penetration would last, e.g., for about one month in July and August and three months in January (Milne and McKay, 1982). If a war would take place in the growing season, agricultural production would be much reduced because of lack of sunlight. Much cultivated land might actually burn before that. Survivors of the nuclear holocaust could, therefore, suffer much from both famine and adverse atmospheric conditions.

The atmospheric, vertical temperature profile and many other meteorological conditions would change profoundly. Under normal conditions, most of the solar radiation, which is not scattered back to space, is absorbed at

the earth's surface. This leads to the observed decrease of temperatures with height in the troposphere. Under the immediate post war conditions, the surface is no longer heated by solar radiation below the smoke clouds and land surfaces are bound to cool. This occurs rapidly (Hunt, 1976). As an example of this, the decrease of insolation due to the arrival in Washington, D.C., of smoke layers from Canadian forest fires in late September, 1950, caused surface temperatures to drop by 2-4°C (Wexler, 1950).

Various types of models may be applied to estimate the meteorological effects of a nuclear war. Detailed one-dimensional model calculations, which take into account aerosol coagulation, convection, condensation and radiative transfer of solar and terrestrial radiation, have been performed by Turco *et al.* (1983). The effects of soil derived, submicron dust particles which are formed by ground bursts and deposited high in the atmosphere, were also considered. For conditions closely corresponding to the Ambio scenario, Turco *et al.* (1983) calculated a rapid cooling by about 35°C, resulting in freezing conditions over the continents which would last for several weeks to months. For most locations and times such freezing conditions, together with the lack of sunlight, would be catastrophic to many plant and animal species, as well as entire ecosystems. Such conditions would rapidly develop over land. The much larger heat capacity of the ocean surface layers would sustain much more normal temperatures over the oceans and in coastal areas.

It is difficult to predict the meteorological behavior of the atmosphere under such conditions, for which we need detailed three-dimensional models. We may, however, guess that in the low atmosphere winds would blow from the continents to the much warmer oceans. Upward motions develop over the oceans, accompanied by fog and precipitation, especially over coastal waters. This could provide the most efficient removal mechanism for the aerosol in the atmosphere. A return flow would occur aloft, carrying water vapor to the continents, which would precipitate as snow. Over the cold lands extensive areas could also be covered with supercooled fogs, which would be very damaging to vegetation. Also here the aerosol may be removed from the lower atmosphere. However, much light absorbing smoke would probably remain far above this ocean-land circulation system and its removal by precipitation scavenging might well be very inefficient.

The plausibility of the results of Turco *et al.* (1983) can be demonstrated with simple radiative equilibrium models, in which we assume that all smoke is evenly distributed above the 750 mb level in the atmosphere, the remaining layer closest to the ground being smokefree (see Figure 3).

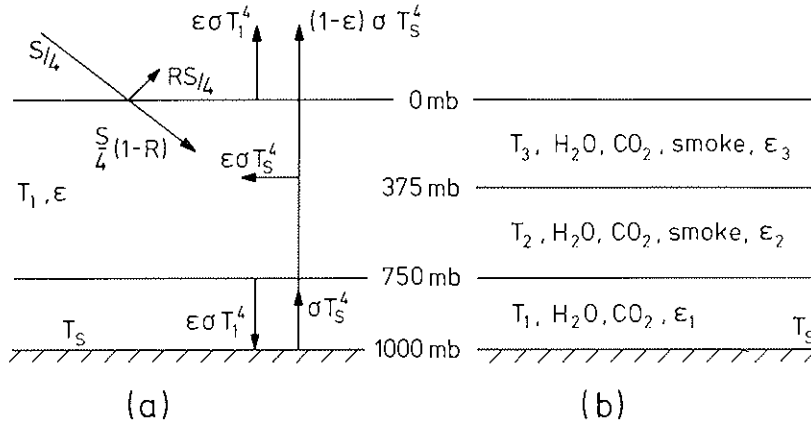

FIG. 3. Assumed partition of atmosphere in layers for two radiative equilibrium models; a) infrared transfer by atmospheric gases neglected; b) infrared transfer by H_2O and CO_2 taken into account.

The assumption about the location of the smoke is quite arbitrary, but soot probably reaches the greatest heights. In the simplest demonstration we neglect the effect of clouds and of infrared radiation by the atmospheric gases CO_2 and H_2O and consider only the effect of the smoke on the transfer of solar and infrared radiation. The layer between the ground and 750 mb is, therefore, assumed to be totally transparent to all radiation. The surface and smoke layer temperatures are T_s and T_1, respectively. The smoke layer is assumed so opaque in the visible that most solar radiation is absorbed by the black smoke. In the infrared, however, the specific absorption is about ten times smaller (Chylek *et al.*, 1981; Roessler and Faxvog, 1979), so that we take the IR emissivity (ε) to be equal to 0.1. The radiative equilibria for the surface and smoke layer for average conditions are given by the formulae (see Figure 3):

$$\varepsilon \sigma T_1^4 = \sigma T_s^4 \tag{12}$$

$$(1 - R)\, S/4 + \varepsilon \sigma T_s^4 = 2\, \varepsilon \sigma T_1^4 \tag{13}$$

with S = solar constant (1360 W/m^2), σ = Stefan-Boltzmann constant (5.7×10^{-8} Wm^{-2} K^{-4}) and R the reflectivity of the smoke layer, which equals about 0.1 according to formula (10).

Solving equations (12) and (13) we obtain

$$T_1 = 413\ \text{K} \text{ and } T_s = 232\ \text{K}$$

The ground temperature without the presence of smoke is calculated from the formula

$$\sigma T_1^4 = (1 - R)\, S/4 \tag{14}$$

If here we take also R = 0.1, a typical value for tbe earth's surface, we obtain T_s = 273 K. The presence of the smoke layer causes, therefore, a cooling of the surface by about 40°C, in good agreement with tbe results of Turco *et al.* (1983).

A more realistic, but still simple, radiative equilibrium model may be developed by taking into account also the effects of infrared radiation absorption by water vapor and carbon dioxide. Absorption of solar radiation by atmospheric gases is neglected. For tbis case we divide the atmosphere in three layers: a cloud-free one between 1000 mb and 750 mb, and two layers containing equal amounts of smoke above the 750 mb level (see Figure 3). In this case the transfer of solar radiation by the aerosol layers is treated with the method of Sagan and Pollack (1967), as described before. The specific scattering and absorption of smoke were taken equal to 4 m^2/g and 2.2 m^2/g respectively. The radiative properties of smoke in the infrared were based on the data by Roessler and Faxvog (1980) and Shettle and Fenn (1979), adopting an elemental carbon content of 22% (see Table VI). The emissivities of water vapor and carbon dioxide were mostly based on the works of Ramanathan (1976) and Rodgers and Walshaw (1966). The effects of clouds were still neglected. More details about the model are given in the appendix. The results of the calculations are presented in Figure 4, in which the calculated radiative equilibrium temperatures for the ground (T_s), the smokefree 1000-750 mb layer (T_1) and the two smoke layers between 750 and 375 mb (T_2) and above 375 mb (T_3) are plotted as functions of the mass of smoke per unit area. For small optical depths of the smoke, the results are sensitive to the assumed albedo of the earth's surface. For this reason results are shown for ground reflectivities of 0.3 and 0.5. The latter value would apply for dirty snow with a soot to ice ratio of about 10^{-5} (Chylek *et al.*, 1984), which would apply for the immediate post nuclear war conditions. For small optical depths a sharp temperature discontinuity is calculated at the surface of the earth. This is typical for radiative equilibrium model results, which can not take

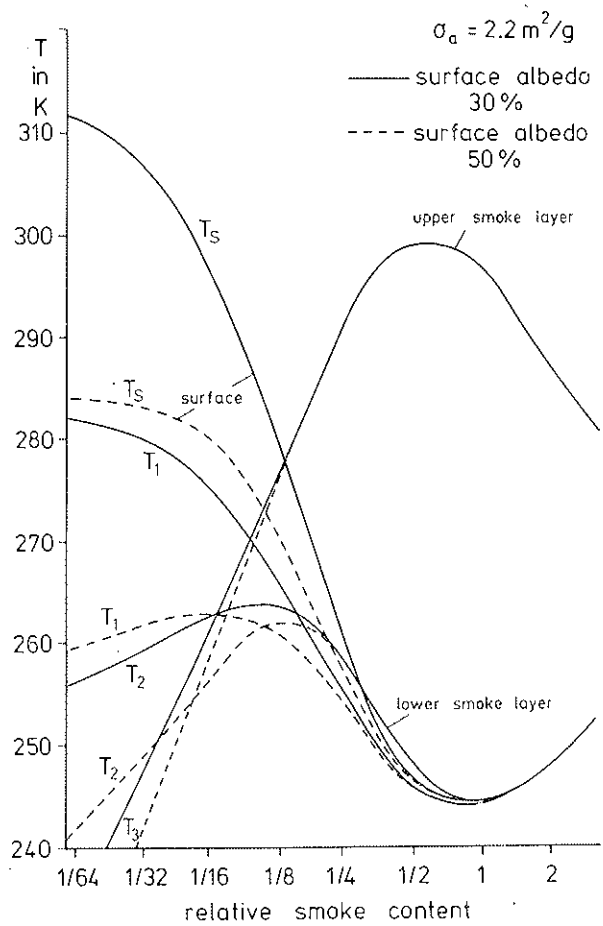

FIG. 4. Calculated temperature at the earth's surface (T_s) and in three atmospheric layers (T_1, T_2 and T_3) as function of the atmospheric smoke content. A relative smoke content of unity corresponds to 1.2 g of smoke per m² surface area. Two sets of calculations are presented for hypothetical surface albedos of 30% and 50%.

into account the transfer of sensible and latent energy from surface to atmosphere.

The model results show a large cooling by about 50°C of the ground and the lower atmosphere due to the introduction of smoke up to an average coverage of 1.2 g/m², which accidentally corresponds to the uniform distribution of 310 million tons of smoke (Table VI) over the northern hemisphere. For larger smoke coverage ground temperatures

actually increase slightly as the smoke no longer influences the short wave radiation field, but reduces the escape of infrared radiation to space. The upper smoke layer would heat up to temperatures which are normally found at the earth's surface. The entire temperature profile is thereby turned upside down and an enormous inversion develops over the entire depth of the troposphere, particularly over the continents. This reduces convection, vertical mixing and precipitation. Under such conditions fire produced air pollutants would remain airborne much longer than under natural conditions (Crutzen and Birks, 1982).

In order to indicate the sensitivity of the model to changes in the optical properties of the aerosol, Figure 5 shows results obtained with the same model, but for two times smaller smoke absorption cross sections (1.1 m^2/g aerosol) in the visible. We see that the results differ only in details from those shown in Figure 4. Similar results were also obtained for an absorption cross section of 0.6 m^2/g aerosol. These lower values apply for aerosol with appreciably lower EC content.

The sensitivity of the results to the ground reflectivity may be of particular importance, as we may expect extensive cloud cover and snowfall to develop over the continents. This would accelerate the cooling of the earth's surface and substantially delay and maybe even prevent a return to normal climatic conditions.

Because of the simplicity of the model, the results obtained with it should not be overinterpreted. Figure 4 suggests, however, that even ten times less smoke than calculated in Table VI, could still lead to 20°C colder continental surface temperatures.

The simple climate equilibrium models presented above provide, therefore, the essentials of the results of the more elaborate and accurate model of Turco *et al.* (1983). However, even this model is clearly limited as it is one-dimensional and averages globally over horizontal surfaces. To estimate the meteorological effects of a nuclear war it is necessary to use interactive multi-dimensional, dynamical models of the atmosphere. Simplified computations with such models have already been carried out at three research centers in the US and USSR. Some preliminary calculations with two-dimensional (McCracken, 1983) and three-dimensional climate models (Alexandrov, 1983; Covey *et al.*, 1984) support the findings derived with the simpler models and point to the possibility that winter conditions may occur in July especially over North America, the Soviet Union, China and large parts of India.

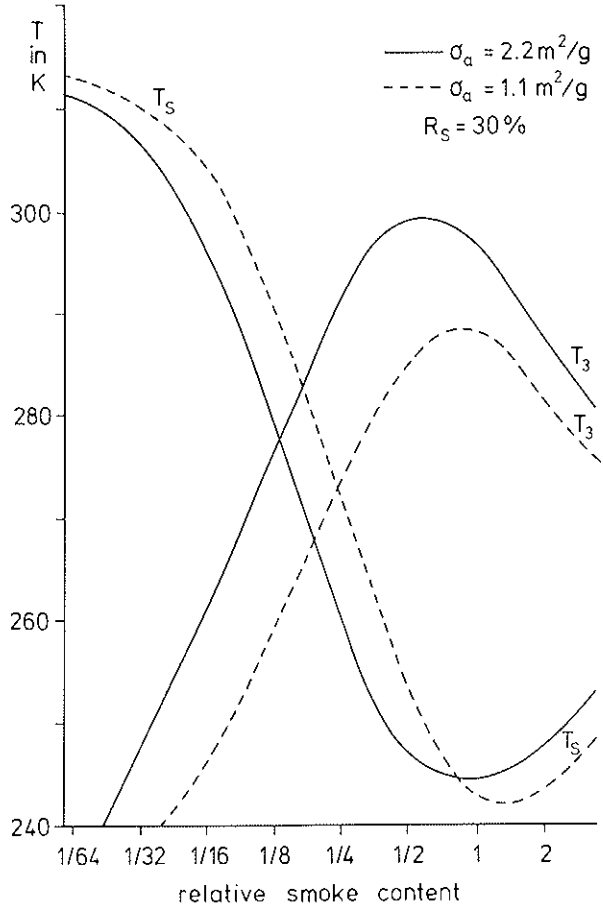

FIG. 5. Calculated temperatures in top smoke layer (T_3) and at the earth's surface (T_s) for specific absorption cross sections of 1.1 and 2.2 m^2/g aerosol in the visible. Assumed albedo at the earth's surface 30%.

8. ADDITIONAL ATMOSPHERIC EFFECTS (BRIEF INDICATIONS)

a) For the immediate period following the nuclear war, the atmosphere would become loaded with many unusual pollutants such as hydrogen chloride which is produced by the burning of polyvinyl-chloride (PVC), which material is used extensively in modern buildings. During the first months following the war, the removal of HCl, HNO_3, H_2SO_4 and other fire effluents may lead to precipitation with a pH of only about 3. Over

land a dirty, supercooled drizzle may become established, which, together with other air pollutants, would be detrimental to biosphere and survivors.

b) Through nuclear explosions and fires there will also be a temporary strongly enhanced production of NO. We estimate that the total may amount to about 10^{14} gram of NO. In the dark atmosphere NO will be mainly converted to NO_2, which is a relatively strong absorber of solar radiation. We estimate that the optical depth caused by the fire and fireball produced NO_2 may be close to half, reducing the average penetration of sunlight to the ground by another factor of almost three for wavelengths below 500 nm.

c) If a substantial amount of the dark aerosol would reach altitudes above 25 km, the formation of ozone by the photodissociation of molecular oxygen would be much suppressed, as the active solar radiation below 240 nm would be strongly absorbed by the soot particles with a specific absorption cross section of maybe 20-30 m^2/g EC. Also, not only the smoke could reach the stratosphere, but also gaseous (e.g. NO_x, H_2O and HCl), and maybe particulate compounds, which destroy ozone catalytically. The higher than normal temperatures which would result because of absorption of solar radiation by soot in the stratosphere, will also strongly enhance ozone loss reactions. Severe ozone depletions may, therefore, take place. The effects of enhanced UV-B (290-320 nm) solar radiation fluxes on the biosphere can be substantial and have been studied especially in connection with the concurrence of non-melanoma skin cancer in the white race. A 1% reduction in total ozone will on the average lead to a 2% increase in the UV-B radiation flux, so that there is an optical amplification factor of two. A statistical analysis of the skin cancer incidence in the US indicates an additional biological amplification factor of about two, so that a reduction in the total ozone by about 1% would lead to a 4% increase in non-melanoma skin cancer (Scotto *et al.*, 1982). Although for humans the UV-B problem is small in comparison to the afore described much more serious environmental consequences of a nuclear war, other parts of the biosphere (e.g. the marine phytoplankton communities) are very susceptible to increased UV fluxes (NAS, 1982). It should be noted that the total solar radiation at ground level could very well be smaller than normal (due to the presence of soot in the atmosphere), while at the same time the UV-B component of the solar flux is larger. This is due to the strong sensitivity of UV-B radiation levels to changes in total ozone.

d) The deposition of the aerosol on the earth's surface may cause

additional environmental and climatic stress. Crutzen and Birks (1982) pointed out the possibility of enhanced snowmelting in permanent glaciers. A recent study by Chylek *et al.* (1984) on the albedo of soot-contaminated snow may be used to obtain an idea of its potential importance. If 10^{14} g EC is deposited in the northern hemisphere over a period of one month, the average EC content in precipitation would be about 10^{-5}. Such a concentration of soot in snow would advance complete snowmelt by about one month. Alexandrov (1983) has already pointed to the risk of melting of snow and glaciers, leading to continental flooding due to the occurrence of above freezing air temperatures at high altitudes.

e) It is also quite possible that fallout of the large amounts of dark aerosol will lead to a substantial reduction in photosynthesis in the upper layers of the oceans and lakes. Under normal conditions, filter-feeding zooplankton very actively remove small-sized mineral and organic particles in a matter of weeks from the euphotic layer to the deep sea through their excretions (Delany, 1967; Alldredge and Madin, 1982; Degens and Ittekott, 1983; Deuser *et al.*, 1983 a,b). After the darkness period following a nuclear war, this biological cleansing mechanism may be much disturbed, so that oceanic productivity may remain reduced over considerable time, even after the clearing of the atmosphere. Another negative factor contributing to this may be that fire produced aerosols contain large amounts of harmful pollutants, e.g. trace metals (Hardy and Crecelius, 1981) and radioactive material.

f) Even after the initial fires have stopped burning, during the years following the nuclear war frequent fires would occur in the forested areas which were destroyed by fires, cold temperatures and radioactive fallout. It is well known that forest fires may burn the same area several times over in intense fires of dead and very flammable forest materials (Plummer, 1912). The forest area damage by radioactivity alone may be three times larger than caused by the immediate fires (Galbally *et al.*, 1983; Woodwell, 1982).

g) Although large quantities of reactive hydrocarbons which are produced by the fires would remain available after the atmosphere is cleansed from smoke, the production of ozone by photochemical reactions is dependent on the availability of sufficient quantities of the NO_x gases. Because these gases or their reaction products, may be absorbed on the smoke particles, tropospheric ozone production might not occur to the extent estimated by Crutzen and Birks (1982). High ozone concentra-

tions could, however, appear at the earth's surface due to much enhanced downward transport of ozone from the stratosphere in smoke-free regions, which could compensate for the upward motions which are stimulated by the solar heating of the black smoke clouds.

9. Conclusions

The very serious environmental effects of a total nuclear war as presented by Crutzen and Birks (1982) and evaluated further in this and other very recent papers (Turco *et al.*, 1983; Covey *et al.*, 1984; McCracken, 1983; Alexandrov, 1983) are surprisingly new scientific discoveries. In the event of a war, it is quite likely that for weeks sunlight will be much reduced over extended areas of the Northern Hemisphere by the production of several hundred million tons of long-lived aerosol which scatters, and most importantly, absorbs sunlight. This is possible because of the burning of huge amounts of combustibles in cities and industries. The meteorological and ecological consequences of such atmospheric aerosol loading could be severe. The continents would cool and the overlying atmosphere warm, effectively wiping out the troposphere and creating very stable thermal conditions in the lower atmosphere. Above the smoke clouds the atmosphere would become much more destabilized. A combination of cold temperatures and darkness would strongly diminish agricultural and biological productivity, adding enormously to the problems of the survivors of the war. Important ecosystems, including tropical and subtropical forests, might become endangered and many plant and animal species might disappear from the earth. We note that we are here dealing with global (or at least hemispherical) effects which could also affect nations which would not be directly involved in the war. The environmental effects have been treated by Ehrlich *et al.* (1983) and especially by Harwell (1984).

We have demonstrated our arguments on the basis of the Ambio (1982) war scenario, using much simplified rainout, aerosol physics and radiative equilibrium models. Our analysis of the amounts of burned materials and smoke production is likewise uncertain and no doubt can be much improved upon, but we have tried to avoid extreme assumptions. It is very hard to carry out sensitivity analyses in this new research field with so many uncertainties. It is quite possible to forward arguments for a much less severe impact of a nuclear war. For instance, one may propose

much more efficient rainout of aerosol. Worse inpacts are also possible. We left out the burning of coal dumps and the consequences of long lasting fires in gas and oil wells, and forests, many of which might become especially vulnerable to fires due to damage by darkness, freezing and radioactive fallout damage (see Galbally *et al.*, 1983; Woodwell, 1982; Ehrlich *et al.*, 1983). We also neglected the albedo effects of soil derived dust in our radiative transfer calculations. The numerical results of this study should, therefore, not be taken too exactly. However, it is hard to discount the possibility that for most survivors of a nuclear war and life on earth as a whole, meteorological and climatic conditions could become extremely hostile. The Ambio war scenario employs 40% of the entire nuclear weapons arsenals of the world, about equally aimed at industrial/urban military targets. Smoke production is, however, far from proportional to total weapon use. For instance, an analysis of the USSR population distribution and industrial capacity showed that the 50 largest cities contained 33% of the urban population and 40% of the industrial capacity. For the largest 300 cities the corresponding numbers increased only to 60% and 65%, respectively (Kemp, 1974). As a consequence, a nuclear war in which "only" 10% of the nuclear arsenals were used against population and industrial centers, could still yield half of the smoke derived for the Ambio scenario. Referring to the results of Figure 4, this could still lead to a lowering of the continental surface temperatures by 40°C. Turco *et al.* (1983) have concluded that a "small" 100 Mt nuclear war, mainly aimed at major cities, could cause severe climatic perturbations.

Our findings have, therefore, clear military implications. They indicate that a one-sided attack by one of the superpowers might well lead to the destruction of the attacking side itself and many other nations because of worldwide destruction of life support systems and environment, as a consequence of large scale, severe disturbances of the atmosphere due to smoke and dust emissions. It is important that these effects are better quantified and studied with more appropriate models. We hope that this paper will lead to the involvement of other scientists to improve the simple analyses presented in this paper and to participate in studies of the atmospheric, biological and ecological consequences of nuclear war, so that all governments can be thoroughly informed of them.

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DISCUSSION

MARINI-BETTÒLO

I think that your model proposed can be also applied to the movement of the particulates in general also through space.

CRUTZEN

Yes. I think one of the major drawbacks with a model like this is that it is really based on too much experience with normal conditions, and when you get a situation like this with an enormous stability in the lower atmosphere, basically the troposphere suddenly is gone and becomes stratosphere. I think we have to revise any model which we have developed so far, and there are several reasons to believe that the situation could be worse than I pictured here. The high stability of the lowest layers of the atmosphere may mean that aerosol will remain in the atmosphere much longer than we are used to under normal conditions. It is also very easy to calculate the heating rates which one would get in the dust or in the smoke clouds when they are heated by the sun. I did that and you get 30°C per hour. That means that these clouds are just not going to lie there, nice and stable, they are going to move upwards; so I think it is a very serious possibility that the smoke clouds will come up in very high levels in the atmosphere and can be transported globally. So even the Southern Hemisphere might not be safe from conditions which are indicated here.

MARINI-BETTÒLO

You indicate the limits to the use of these models, but that because you have high concentrations of soot and particulates all over. If you use the same model to not so high concentrations, as it happens, for instance in a sand storm, and so on, it would it apply better?

CRUTZEN

Yes, it would be more applicable, but I have never developed a model for a particular situation like that. The models which I have developed are for global dispersions, say, of fluorocarbons, or of stratospheric aerosol, normal situations which we could test with observations in the atmosphere.

CANUTO

Just a clarification. The blast area of bombs does not increase linearly with the megatonnage of the bomb. It increases with the power of two-thirds if I am correct. In other words, 100 one-megaton bombs do more damage than one bomb of 100 megatons. How does one then scale your result if you want to make it worse; in other words you use .4 megatons — and you want to compare your result with the one of Brian Toon who has not used the same number of megatons. In other words, it is difficult to scale your number.

CRUTZEN

I think that on the average — I have to look up the numbers, but actually the average size of the bombs is 0.5 megatons — mine was 0.4. So we are not so far off.

CANUTO

Did the blast area come in any way in your computations?

CRUTZEN

No, the blast area I neglected. Everything is determined by the heat radiation, and this is based on experiences from the past. So — I think I have been on the conservative side there.

MALONE

I would like to congratulate Dr. Crutzen on one of the most impressive papers that I have heard in the last 43 years. With regard to its policy implications, it stands certainly in a class all by itself. I would simply underscore Dr. Crutzen's emphasis on the conservativeness of his estimates. Having looked at thousands of vertical temperature profiles, it is clear, I believe, that the residence time will be of about an order of magnitude difference between the stratosphere rather than the troposphere, and also the lapse rates, would no longer apply. So as you say, it is just an entirely different atmosphere. This would inhibit the precipitation and the fallout, so that I just really wanted to underscore the conservative nature of your calculations.

I have three questions. It was not quite clear to me whether you took the whole globe or just the Northern Hemisphere into account. When you calculated

the spread of the smoke cloud, soot cloud, was it just the Northern Hemisphere, or was it the globe?

CRUTZEN

No. The few explosions in the Southern Hemisphere I neglected in this study, so I took the targets in the Northern Hemisphere and assumed that they were initially between 30° north and 60° north. Then they started spreading out over the Northern Hemisphere, but in 30 days according to this model did not reach the Southern Hemisphere. In a real case I doubt very much whether that would be the case, probably it would reach the Southern Hemisphere, because the sooty smoke world absorb so much solar energy that the heated atmosphere would move upward and southward much faster than is normally the casi.

MALONE

My second question is: did you speculate at all on the likely consequences of the baroclinicity which would be established between the marine and the continental areas — that would probably be quite large.

CRUTZEN

I can speculate about it, and my guess is that firstly the calculations seem to indicate that freezing temperatures over land may very well occur. On the other hand, over the oceans, because of the high thermal capacity of the surface waters, the ground or the near-surface temperatures would be higher; so what probably would occur is that there would be an uprising motion over oceanic regions, compensated by sort of high pressure régime, over land areas. How far those circulation systems will extend into the troposphere is very much dependent on where the soot layers will be. If they are very low, then I can imagine that one gets soot ont of the circulation. If they are high up, then I think the soot layers, independent of where they are — over the land or over the ocean — will start setting up some sort of circulation of their own. I do not see how we can estimate that reasonably at the moment. The other thing which one has to look at is the possibility that a land-sea breeze situation may be set up between oceans and lands. There will still be humidity brought into the land areas and there will be, I think, developing a rather shallow circulation. And with freezing temperatures near the ground,

I think one will develop cold fog — super-cool fog which of course in itself may mean an enormous hazard to vegetation. This is a hting we have not discussed so far, but that could be extremely hazardous for land vegetation.

MALONE

The third question: I was not quite able to determine how long the diminution in the radiation would inhibit photosynthesis. Would it be a matter of days, weeks?

CRUTZEN

The 2% level seems to be the compensation point for many plants, and now it becomes a very large function of the rain-out times which one applies to the models. If a ten-day rain-out time is applied, then already after two weeks most blank communities may be above the 2% compensation point. If a 30-day applies, or longer, then we have the low compensation points conditions for an extended period of time, and that would mean that simply many ecosystems are consuming themselves and will shrink. Agricultural productivity most likely one can forget about in a situation like this.

CANUTO

Could you invert your computations applied to the tertiary, 75 million years ago, to the disappearance of dinosaurs? In this case we do know that something happened but we do not know the megatons.

CRUTZEN

Yes. Of course this sort of calculations and the models which are applied here by Sagan and Toon were firstly developed for the dust storms on Mars. Low temperatures were discovered as soon as the dust started blowing. That was one point; but they later applied it also for the extinction of dinosaurs.