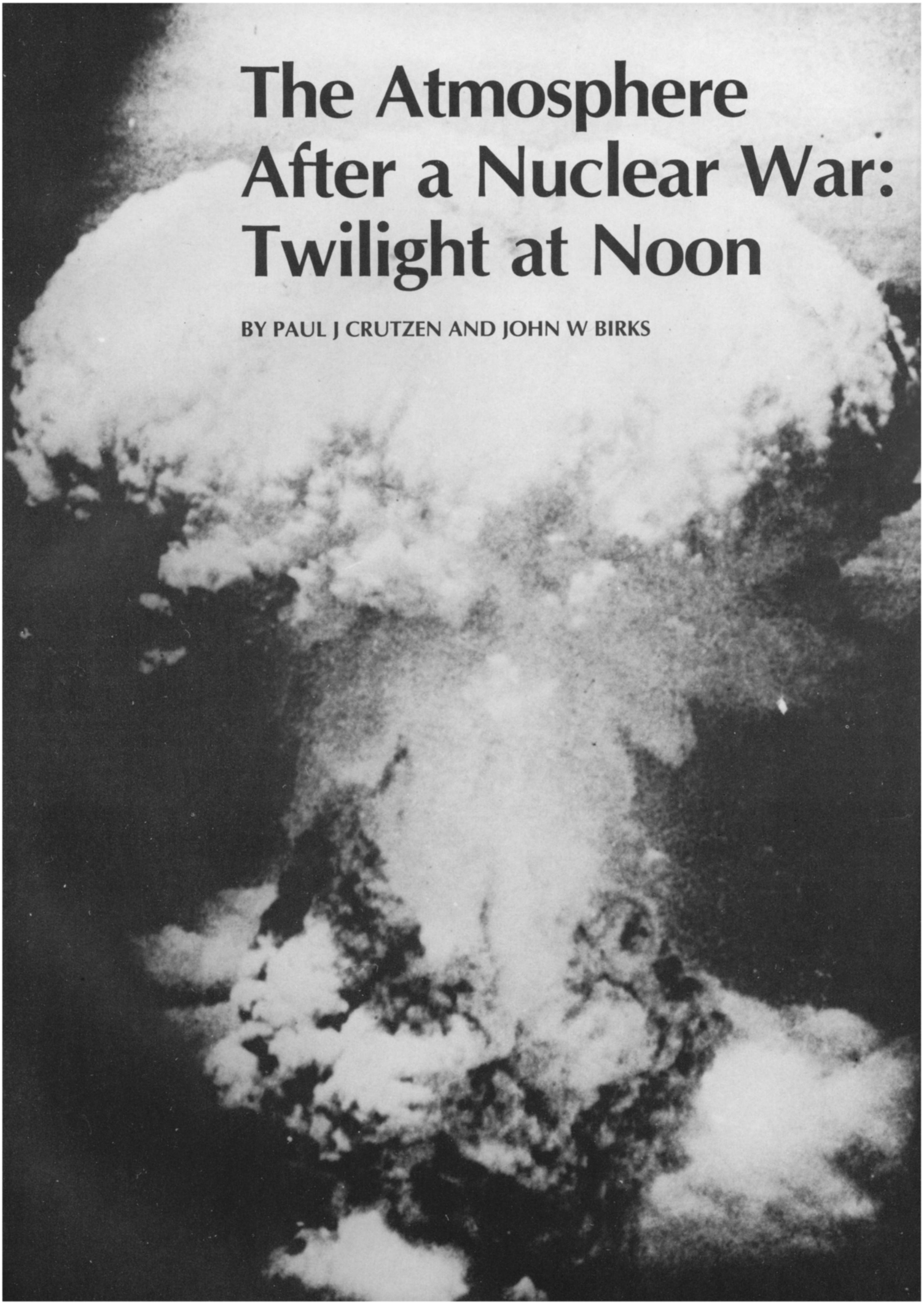
The Atmosphere After a Nuclear War: Twilight at Noon

BY PAUL J CRUTZEN AND JOHN W BIRKS



As a result of a nuclear war vast areas of forests will go up in smoke—corresponding at least to the combined land mass of Denmark, Norway and Sweden. In addition to the tremendous fires that will burn for weeks in cities and industrial centers, fires will also rage across croplands and it is likely that at least 1.5 billion tons of stored fossil fuels (mostly oil and gas) will be destroyed. The fires will produce a thick smoke layer that will drastically reduce the amount of sunlight reaching the earth's surface. This darkness would persist for many weeks, rendering any agricultural activity in the Northern Hemisphere virtually impossible if the war takes place during the growing season.

The immediate effects of a global nuclear war are so severe that any additional long-term effects might at first thought be regarded as insignificant in comparison. However, our investigation into the state of the atmosphere following a nuclear exchange suggests that other severely damaging effects to human life and the delicate ecosystems to which we belong will occur during the following weeks and months. Many of these effects have not been evaluated before.

Previous investigations of the atmospheric effects following a nuclear war have been concentrated primarily on the expected large depletions of ozone in the stratosphere (1,2). Reduction of the stratospheric ozone shield allows increased levels of harmful ultraviolet (uv) radiation to penetrate to the surface of the earth. Such ozone depletion results from the injection of oxides of nitrogen (NO_x) by large nuclear weapons having yields greater than one megaton. Should the nations having nuclear arsenals choose to use their large warheads in a nuclear war, then the earth's protective ozone layer would be much depleted, and the consequent adverse effects associated with the increased flux of ultraviolet radiation would occur. Our conclusions for such a scenario concur with those found in the 1975 report of the US National Academy of Sciences (1).

As assumed in Ambio's reference scenario, it is now believed that the most likely nuclear war is one in which few weapons having yields greater than 1 Mt are used, with preference given to the detonation of large numbers of smaller yield weapons. For such a nuclear war, very little NO_x would be injected above 15 km into the stratosphere by the nuclear bursts, and thus depletion of the ozone layer would not occur as a direct result of the explosions. Nonetheless, other profound effects on the atmosphere can be expected.

In discussing the state of the atmosphere following a nuclear exchange, we point especially to the effects of the many fires that would be ignited by the thousands of nuclear explosions in cities, forests, agricultural fields, and oil and gas fields. As a result of these fires, the loading of the atmosphere with strongly light absorbing particles in the submicron size range (1 micron $= 10^{-6}$ m) would increase so much that at noon solar radiation at the ground would be reduced by at least a factor of two and possibly a factor of greater than one hundred. In addition, fires inject large quantities of oxides of nitrogen and reactive hydrocarbons, the ingredients of photochemical smog. This creates the potential for photochemical smog throughout much of the Northern Hemisphere which may persist for several months after the particulate matter has been deposited on the ground. Such effects have been largely overlooked or not carefully examined in previous considerations of this problem. They are, therefore, considered in some detail in this study.

NUCLEAR WAR SCENARIOS

The explosion of nuclear weapons produces oxides of nitrogen by heating air to temperatures well above 2000 K. When the major constituents of the air—nitrogen and oxygen—are heated to high temperature, nitric oxide (NO) is formed. The equilibrium between N_2, O_2 and NO is rapidly approached at the temperatures characteristic of the nuclear explosions:

$$N_2 + O_2 \leftrightarrow 2\,NO$$

As the temperature of the heated air falls, the reactions which maintain equilibrium become slow and NO cannot revert to the innocuous oxygen and nitrogen. Consequently, nuclear explosions produce NO in much the same way as it is formed as a pollutant in automobile and aircraft engines. A review of the mechanisms forming NO in nuclear explosions is provided in Appendix I. The oxides of nitrogen are important trace atmospheric constituents and play a very important role in atmospheric photochemistry. They are key constituents in the formation of photochemical smog in the troposphere, and the catalytic reaction cycle leading to ozone destruction is the principal means by which ozone concentrations are regulated in the stratosphere. In Appendix I it is estimated that there are 1×10^{32} molecules of NO formed for each megaton of explosion yield. As will be discussed later, large amounts of nitric oxide would also be formed by the many fires that would be started during a nuclear war.

With regard to direct NO_x formation in nuclear explosions, we consider two nuclear war scenarios. Scenario I is Ambio's reference scenario (3). In this scenario

Table 1. Distribution of NO_x produced by nuclear explosions for Scenario I (x 10^{32} molecules).

Alt. (km)	60°S–30°S	30°S–EQ	EQ–20°N	20°N–40°N	40°N–60°N	60°N–NP	Sum
30	–	–	–	0.7	–	–	0.7
29	–	–	–	0.7	1	–	1.7
28	–	–	–	2.3	1	–	3.3
27	–	–	–	2.3	3	–	5.3
26	–	–	–	2.3	3	–	5.3
25	–	–	–	2.3	3	–	5.3
24	–	–	–	3.7	3	–	6.7
23	–	–	–	3.7	5	–	8.7
22	–	–	–	3.7	5	–	8.7
21	–	–	–	3.7	5	–	8.7
20	–	–	–	2.1	5	–	7.1
19	–	–	–	2.1	2.8	–	4.9
18	–	0.3	1.1	0.1	2.8	–	4.3
17	–	1.1	3.5	10.4	0.2	–	15.2
16	0.7	3.5	10.8	30.7	24.5	–	70.2
15	2.3	8.9	27.5	30.7	72.9	–	142.3
14	2.3	8.9	27.5	116.8	72.9	1.1	229.5
13	3.7	13.0	39.7	247.7	121.5	3.5	429.1
12	8.5	12.1	36.7	225.1	276.6	3.5	562.5
11	16.6	6.6	20.4	329.4	533.5	11.9	918.4
10	14.6	0.5	1.5	327.3	470.2	26.4	840.5
9	24.4	–	–	183.2	775.8	25.0	1 008.4
8	24.4	–	–	13.2	775.8	36.7	850.1
7	13.6	–	–	–	434.4	36.5	484.5
6	1.0	–	–	–	21.0	20.4	42.4
5	–	–	–	–	–	1.5	1.5
Sum	**112.1**	**54.9**	**168.7**	**1 544.2**	**3 618.9**	**166.5**	**5 665.3**

bombs having a total yield of 5750 Mt are detonated. The latitudinal and vertical distributions of the 5.7×10^{35} molecules of nitric oxide produced in these explosions are determined by the weapon sizes and targets projected for this scenario. Since most of the weapons have yields less than 1 Mt, most of the NO_x is deposited in the troposphere, and the effect on the chemistry of the stratosphere is much less than if the bomb debris were deposited mainly in the stratosphere. The assumed NO input pattern for the Scenario I war is provided in Table 1.

The Scenario II war is similar to those used in previous studies by investigators using one-dimensional models and is included here mostly for historical reasons. This scenario considers a total yield of 10 000 Mt uniformly distributed between 20° and 60° in the Northern Hemisphere. The vertical distribution of NO is calculated assuming equal yields of 1-Mt and 10-Mt weapons, *ie* 5000 1-Mt weapons and 500 10-Mt weapons are detonated. For this scenario, equal quantities of NO_x are injected above and below 18 km, as seen in Table 2. Thus, the tropospheric effects for the Scenario II war are similar to those for the Scenario I war. However, the Scenario II war also results in an additional large perturbation of the stratospheric ozone layer.

FIRES

From an atmospheric point of view, the most serious effects of a nuclear war would most likely result from the many fires which would start in the war and could not be extinguished because of nuclear contaminations and loss of water lines, fire equipment and expert personnel. The devastating effects of such fires in urban areas were indicated by Lewis (4). Here we show that the atmospheric effects would be especially dramatic. Several types of fires may rage. Besides the fires in urban and industrial centers, vast forest fires would start, extensive grasslands and agricultural land would burn, and it is likely that many natural gas and oil wells would be ruptured as a result of the nuclear explosions, releasing huge quantities of oil and natural gas, much of which would catch fire. To give an estimate of the possible effects, we will consider as a working hypothesis that 10^6 km^2 of forests will burn (this corresponds roughly to the combined area of Denmark, Norway and Sweden) and that breaks in gas and oil production wells will release gaseous effluents from the earth corresponding to the current rate of worldwide usage. In our opinion these are underestimates of the real extent of fires that would occur in a major nuclear war (see also Box 1).

Gaseous and Particulate Emissions from Forest Fires

In the US and especially in Canada and the USSR, vast forests are found close to important urban strategic centers, so that it may be expected that many wildfires would start burning during and after the nuclear exchange. Although it is hard to estimate how much forest area might burn, a total of 10^6 km^2, spread around in the Northern Hemisphere, is probably an underestimate, as it is only about 20 times larger than what is now annually consumed by wildfires (5). This amounts to 4 percent of the temperate and boreal forest lands, and is not larger than that of the urban areas combined (6). Furthermore, Ward *et al* (7) have pointed out that effective fire control and prevention programs have reduced the loss of forests in the US (exclusive of Alaska) from 1.8×10^5 km^2 in the early 1930's to less than 1.6×10^4 km^2 by the mid 1970's. The US Forest Service is quoted as estimating that a nuclear attack on the US of ~1500 Mt would burn a land area of $0.4–6\times10^6$ km^2 in the US (8). All this information indicates that our assumption of 10^6 km^2 of forest area that could be consumed by fire is not an overestimate.

An area of 10^6 km^2 of forest contains on the average about 2.2×10^{16} g dry matter or about 10^{16} g of carbon phytomass (6) and about 10^{14} g of fixed nitrogen, not counting the material which is contained in soil organic matter. Typically, during forest wildfires about 25 percent of the available phytomass is burned (5), so that 2.5×10^{15} g of carbon would be released to the atmosphere. During wildfires about 75 kg of particulate matter is produced per ton of forest material burned or 450 kg of carbon (7), so that 4×10^{14} g of particulate matter is injected into the atmosphere by the forest fires. Independently, we can use the information by Ward *et al* (7) to estimate the global biomass and suspended particulate matter expected to be produced by wildfires which would be started by the nuclear war. According to these authors the forest area now burned annually in the US, excluding Alaska, is about 1.8×10^4 km^2, which delivers 3.5×10^{12} g particulate matter to the atmosphere. Accordingly, a total area of 10^6 km^2 would inject 2×10^{14} g particulate matter into the atmosphere, which should come from 3×10^{15} g of burned forest material, or 1.3×10^{15} g C. This is a factor of two less than the earlier derived estimate, so we will use a range of $1.3–2.5\times10^{15}$ g of carbon as the global atmospheric gaseous release and $2–4\times10^{14}$ g as particulate matter.

In forest fires most of the carbon is released as CO_2 to the atmosphere. The forest fire contribution to the atmospheric CO_2 content, which totals 7×10^{17} g of carbon, is rather insignificant. The repercussions of the forest fires are, however, much more important for the contribution of other gases to the atmosphere, *eg* carbon monoxide (CO). With a relative release rate ratio CO:CO_2 of about 15 percent (9), the production of CO would amount to $2–4\times10^{14}$ g C, which is roughly equal to or two times larger than the present atmospheric CO content (10). Within a short period of time, average concentrations of CO at midlatitudes in the Northern Hemisphere would increase by up to a factor of four, and much larger CO increases may be expected on the continents, especially

Table 2. Distribution of NO_x produced by nuclear explosions for Scenario II (x 10^{32} molecules).

Alt. (km)	20°N–40°N	40°N–60°N	Sum
31	62	62	124
30	62	62	124
29	188	188	376
28	188	188	376
27	188	188	376
26	188	188	376
25	312	312	624
24	312	312	624
23	312	312	624
22	312	312	624
21	175	175	350
20	175	175	350
19	80	80	160
18	54	54	108
17	80	80	160
16	125	125	250
15	375	375	750
14	375	375	750
13	625	625	1 250
12	625	625	1 250
11	350	350	700
10	25	25	50
Sum	5 000	5 000	10 000

BOX 1.

The attenuations of sunlight at great distances from forest fires have been documented for many years. Phenomena such as "dark days", "dry fog", "Indian summer" and "colored rain" are now attributed to smoke produced by fires in forests, prairies and peat bogs. The great forest fires during October 13–17, 1918 in Minnesota and adjacent sections of Wisconsin produced smoke that had strong optical effects and could even be smelled as far away as the eastern US coast. A report from Cincinnati, Ohio is particularly descriptive (H Lyman, Reference 17): "At 3 PM the smoke and haze became denser, but the sun's light and its disk could be seen until 3:35 PM, at which time the sun was entirely obscured. Objects at this time could not be seen at a distance of 300 feet." More than 100 forest fires in northwestern Alberta and northeastern British Columbia resulted in the "Great Smoke Pall" of September 24–30, 1950 with press reports carrying accounts of smoke being observed as far away as England, France, Portugal, Denmark and Sweden (H Wexler, Reference 17). Most of Canada and the eastern one-third of the continental US were particularly affected. In the eastern US the smoke was confined to the altitude range of about 2.5–4.5 km, so that there was no reduced visibility at the ground. However, the sun was so obscured that it was visible to the naked eye without discomfort and had what was typically described as a violet or lavender color. Measurements in Washington, DC indicated that the solar intensity was reduced by a factor of two on September 25–26 in the absence of clouds.

in regions downwind (generally east of the fires). Accompanying those emissions there will also be significant inputs of tens of Teragrams (1 Teragram = 1 Tg = 10^{12} g) of reactive hydrocarbons to the atmosphere, mostly ethylene (C_2H_4) and propylene (C_3H_6), which are important ingredients in urban, photochemical smog formation. More important, phytomass consists roughly of about 1 percent fixed nitrogen, which is mainly contained in the smaller-sized material such as leaves, bark, twigs and small branches, which are preferentially burned during fires. As a rough estimate, because of the forest fires we may expect an input of 15–30 Tg of nitrogen into the atmosphere (7). Such an emission of NO would be larger than the production in the nuclear fireballs and comparable to the entire annual input of NO_x by industrial processes. Considering the critical role of NO in the production of tropospheric ozone, it is conceivable that a large accumulation of ozone in the troposphere, leading to global photochemical smog conditions, may take place. An increase of ozone due to photochemical processes in forest fire plumes has indeed been observed by several investigators (11, 12).

Particulate Matter from Forest Fires and Screening of Sunlight

The total production of $2–4\times10^{14}$ g of particulate matter from the burning of 10^6 km^2 of forests is comparable on a volume basis to the total global production of particulate matter with diameter less than 3 microns (μm) over an entire year (or 200–400 million tons, 13). The physical and chemical nature of this material has been reviewed (14).

The bulk of the mass (>90 percent) of the particulate matter from forest fires consists of particles with diameters of less than 1 μm and a maximum particle number density at a diameter of 0.1 μm. The material has a very high organic matter content (40–75 percent) and much of it is formed from gaseous organic precursors. Its composition is on the average: 55 percent tar, 25 percent soot and 20 percent ash. These particles strongly absorb sunlight and infrared radiation. The light extinction coefficient, b_s (m), is related to the smoke density, d (g/m^3), by the relationship $b_s = ad$, where a is approximately 4–9 m^2/g (14, 15). With most smoke particles in the submicron size range, their average residence time in the atmosphere is about 5–10 days (13). If we assume that the forest fires will last for two months (16), a spread of $2–4\times10^{14}$ g of aerosol over half of the Northern Hemisphere will cause an average particle loading such that the integrated vertical column of particles is equal to 0.1–0.5 g/m^2. As a result, the average sunlight penetration to the ground will be reduced by a factor between 2 and 150 at noontime in the summer. This would imply that much of the Northern Hemisphere would be darkened in the daytime for an extended period of time following the nuclear exchange. The large-scale atmospheric effects of massive forest fires have been documented in a number of papers (16, 17). Big forest fires in arctic regions are commonly accompanied by huge fires in peat bogs, which may burn over two meters in depth without any possibility of being extinguished (16). The production of aerosol by such fires has not been included in the above estimates.

Gas, Oil and Urban Fires

In addition to the above mentioned fires there are also the effects of fires in cities and industrial centers, where huge quantities of combustible materials and chemicals are stored. As an example, if the European 95-day energy stockpile is roughly representative for the world (18), about 1.5×10^{15} g C fossil fuel (around 1.5 thousand million tons) is stored globally. Much of this would be destroyed in the event of a nuclear war. Therefore, if the relative emission yields of particulate matter by oil and gas fires are about equal to those of forest fires, similar rates of production of atmospheric aerosol would result. Although it may be enormously important, in this study we will not consider the global environmental impacts of the burning and release of chemicals from urban and industrial fires, as we do not yet have enough information available to discuss this matter in a quantitative manner.

Even more serious atmospheric consequences are possible, due to the many fires which would start when oil and gas production wells are destroyed, being among the principal targets included in the main scenario provided for this study (5). Large quantities of oil and gas which are now contained under high pressure would then flow up to the earth's surface or escape into the atmosphere, accompanied by huge fires. Of course, it is not possible for the nuclear powers to target all of the more than 600 000 gas and oil wells of the world. However, certain regions of the world where production is both large and concentrated in small areas are likely to be prime targets in a nuclear war. Furthermore, the blowout of a natural gas well results in the release of gas at a much greater rate than is allowed when under control and in a production network. For example, one of the more famous blowouts, "The Devil's Cigarette Lighter", occurred at Gassi Touil in the Sahara. This well released 15×10^6 m^3 of gas per day until the 200-meter high flame was finally extinguished by explosives and the well capped (19). Fewer than 300 such blowouts would be required to release natural gas (partly burned) to the atmosphere at a rate equal to present consumption. Descriptions of other blowouts such as the Ekofisk Bravo oil platform in the North Sea (20), a sour gas well (27 percent H_2S) in the province of Alberta, Canada (21) and the Ixtoc I oil well in the Gulf of Mexico (22) may be found in the literature.

As an example of how very few weapons could be used to release large quantities of natural gas, consider the gas fields of the

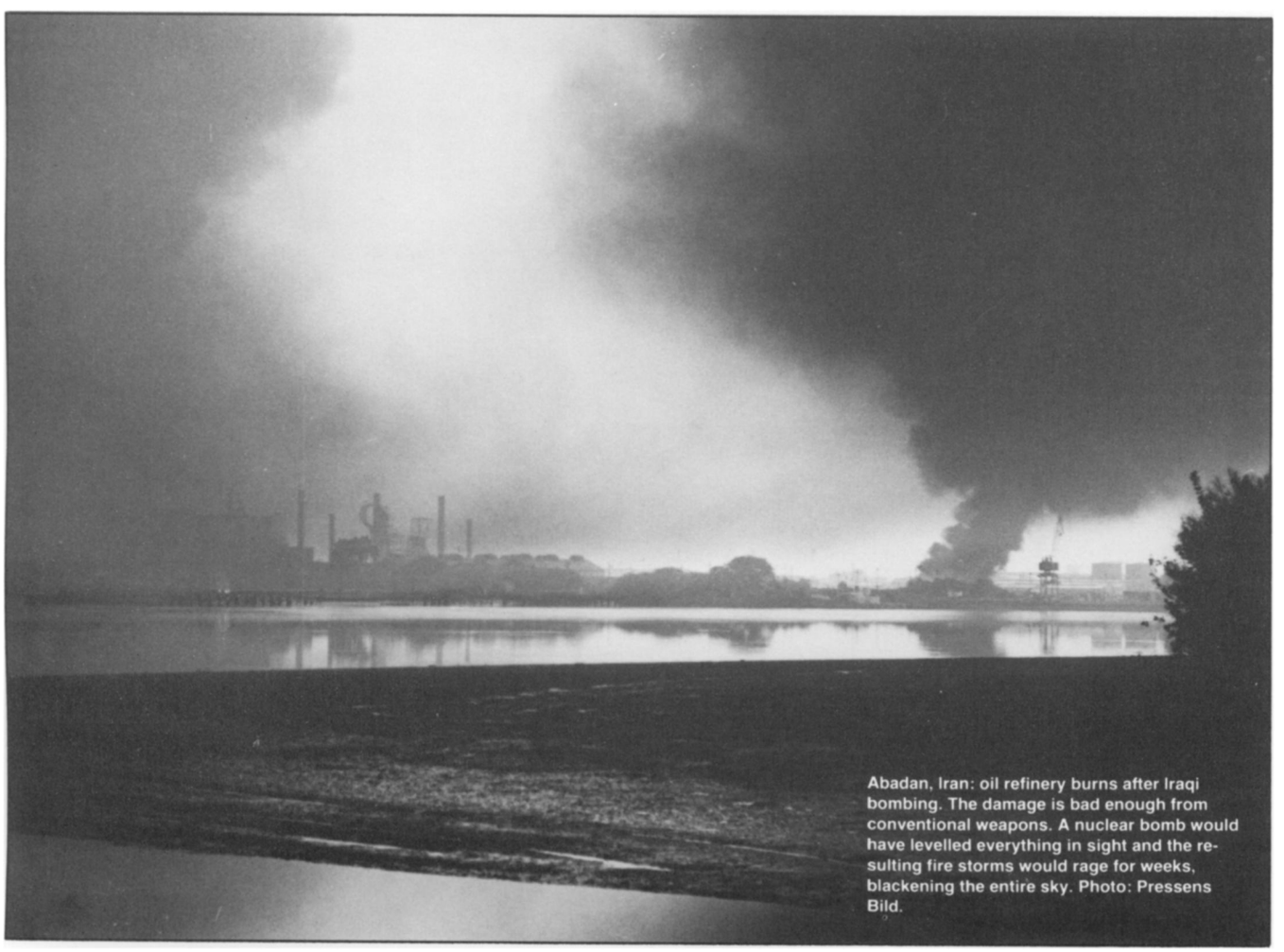
Netherlands. The 1980 production of 7.9×10^{10} m^3 of natural gas in Groningen amounted to 38 percent of that for all of Western Europe and 5 percent of that for the entire world (19). Most of the gas production in the Netherlands is concentrated in a field of about 700 km^2 area. It seems likely that a 300-kt nuclear burst would uncap every gas well within a radius of 1 km either by melting the metal pipes and valves, by snapping the pipes off at the ground by the shock wave, or by breaking the well casings via shock waves propagated in the earth. This is in consideration of the following facts (23): 1) the fireball radius is 0.9 km, 2) for a surface burst the crater formed is approximately 50 m deep and 270 m in diameter, 3) the maximum overpressure at 1 km is 3.1 atmospheres (atm), 4) the maximum dynamic pressure at 1 km is 3.4 atm, and 5) the maximum wind speed at 1 km is 1700 km/h. Considering then that a 300-kt bomb has a cross-section of greater than 3 km^2 for opening gas wells, fewer than 230 such weapons are required to cover the entire 700 km^2 Groningen field of the Netherlands. This amounts to less than 69 Mt of the 5750 Mt available for the Scenario I nuclear war.

Offshore oil and gas platforms might also be targets of a nuclear war. For example, in 1980 the United Kingdom and Norway produced 2.1×10^6 barrels of oil per day from a total of 390 wells (about 40 platforms) in the North Sea (19). Considering that a 100-kt weapon would be more than sufficient to destroy an offshore platform, only 4 Mt of explosive yield need be used to uncap these wells, which produce 3.5 percent of the world's petroleum.

One can point out many other regions of the world where gas and oil production is particularly concentrated. Production in the US is considerably more dispersed than in other countries, however. For comparison, in 1980 the US produced an average of 8.6×10^6 barrels of oil per day from about 530 000 wells whereas the USSR production was 12.1×10^6 barrels per day from only 80 000 wells (19). The oil and gas fields of the Soviet Union, particularly the oil producing Volga-Ural region and the gas and oil fields of the Ob region, are highly localized and particularly vulnerable to nuclear attack.

Much of the gas and oil released as a result of nuclear attacks will burn. This is another source of copious amounts of particulate matter in the atmosphere. However, it is also likely that a fraction of the gas would escape unburned to the atmosphere where it would be gradually broken down by photochemical reactions. Much of the escaping oil may likewise burn, but an appreciable portion of it may volatilize as in the Ixtoc I blowout in the Gulf of Mexico, which resulted in the world's largest oilspill. In this case it is estimated that only 1 percent of the oil burned, while 50–70 percent evaporated (22). We next consider the influence of these emissions on the gaseous composition of the atmosphere.

Natural gas consists usually of a mixture of 80–95 percent (by volume) methane (CH_4) and the remaining 5–20 percent heavier hydrocarbons, mainly ethane (C_2H_6) and propane (C_3H_6), and varying amounts of carbon dioxide and nitrogen. Current global consumption of natural gas amounts to about 10^{15} g of carbon per year, which is 20 percent of the total fossil fuel consumption rate (24). The current atmospheric content of ethane is equal to about 6×10^{12} g of carbon, based on observations indicating amounts of 1 ppbv (1 ppbv $=10^{-9}$ by volume) in the Southern and 2 ppbv in the Northern Hemisphere (25). Consequently the rapid release of C_2H_6 by blow-outs during a nuclear war



Abadan, Iran: oil refinery burns after Iraqi bombing. The damage is bad enough from conventional weapons. A nuclear bomb would have levelled everything in sight and the resulting fire storms would rage for weeks, blackening the entire sky. Photo: Pressens Bild.

BOX 2

Reaction Cycle C1. In the presence of sufficient NO the oxidation of CO to CO_2 results in the formation of ozone as follows:

R1 $CO + OH \rightarrow H + CO_2$
R2 $H + O_2 + M \rightarrow HO_2 + M$
R3 $HO_2 + NO \rightarrow OH + NO_2$
R4 $NO_2 + h\nu \rightarrow NO + O$
R5 $O + O_2 + M \rightarrow O_3 + M$

C1 $CO + 2\,O_2 \rightarrow CO_2 + O_3$

Reaction Cycle C2. The oxidation of methane in the atmosphere leads to ozone formation as follows:

R6 $CH_4 + OH \rightarrow CH_3 + H_2O$
R7 $CH_3 + O_2 + M \rightarrow CH_3O_2 + M$
R8 $CH_3O_2 + NO \rightarrow CH_3O + NO_2$
R9 $CH_3O + O_2 \rightarrow CH_2O + HO_2$
R3 $HO_2 + NO \rightarrow OH + NO_2$
R4 $NO_2 + h\nu \rightarrow NO + O$ (Twice)
R5 $O + O_2 + M \rightarrow O_3 + M$ (Twice)
R10 $CH_2O + h\nu \rightarrow CO + H_2$

C2 $CH_4 + 4\,O_2 \rightarrow CO + H_2 + H_2O + 2\,O_3$

Reaction Cycle C3. In the absence of sufficient NO in the atmosphere the oxidation of CO leads to ozone destruction as follows:

R1 $CO + OH \rightarrow CO_2 + H$
R2 $H + O_2 + M \rightarrow HO_2 + M$
R11 $HO_2 + O_3 \rightarrow OH + 2\,O_2$

C3 $CO + O_3 \rightarrow CO_2 + O_2$

can increase by many-fold the atmospheric concentrations of this gas, which has an atmospheric residence time of about two months. Similar conclusions can be drawn with regard to the higher hydrocarbons. Although relative increases of methane in the atmosphere will take place at a relatively slower pace—as its present atmospheric abundance is much larger, 3×10^{15} g of carbon—even here the atmospheric concentrations may multiply if a sufficiently large percentage of the gas wells are being destroyed. Once destroyed, it seems unlikely that quick repair can be possible in a chaotic world in which little expert personnel and equipment will be available, while the fields will furthermore be heavily contaminated with radioactivity.

Of course it is impossible to guess how many oil and gas well destructions would result from a nuclear war, how much gas will burn and how much will escape unburned to the atmosphere. As an example to indicate the atmospheric effects, let us assume that quantities of oil and gas will continue to burn corresponding to present usage rates, with 25 percent of the present production gas escaping unburned into the atmosphere. We do not know whether the latter assumption is realistic. If not, the chosen conditions may represent a gross underestimate of the atmospheric emissions which could take place during and after a nuclear war. This is, of course, especially the case when the world's oil and gas production fields are targeted as foreseen in the main scenario of this study. We simulate NO_x emissions from oil and gas field fires with those provided by current industrial rates. This adds 20 Tg of nitrogen to the NO_x source from forest fires.

TROPOSPHERIC PHOTOCHEMISTRY

For the Scenario I nuclear war most of the bomb cloud remains in the troposphere. The sudden input of a large quantity of nitric oxide of 5.7×10^{35} molecules (12 Tg nitrogen) by nuclear explosions and the more gradual input of NO_x from forest fires and gas and oil well fires, mainly in the Northern Hemisphere, will cause important changes in the course of the photochemical reactions taking place. Of course, these reactions should occur only in regions where sufficient sunlight would still penetrate. Alternatively, these reactions begin to occur after an appreciable fraction of the aerosol loading of the atmosphere has diminished because of removal of the particulate matter by rain or dry deposition. The following discussion is, therefore, mainly aimed at illustrating the sort of photochemical effects that may take place. The presence of NO in the troposphere favors chemical processes leading to the production of ozone, *eg* during the oxidation of carbon monoxide (CO) and methane (CH_4), which are present at part per million levels as normal constituents of the troposphere. The production of ozone in these cases takes place with OH, HO_2, NO and NO_2 as catalysts via the cycles of reaction C1 and C2 shown in Box 2. Under present non-war conditions, it appears that a large fraction of the troposphere does not contain enough NO for ozone production to take place. For such conditions the oxidation of CO occurs instead via the reaction cycle C3 of Box 2. In contrast to reaction cycle C1, cycle C3 leads to ozone destruction. From a comparison of reaction cycles C1 and C3, it follows that ozone production takes place as long as the atmospheric concentration of NO exceeds 1/4000 that of O_3, which is the ratio of rate coefficients for the reactions R11 and R3 (26, 27). If enough NO were present everywhere in the troposphere for all atmospheric oxidation of CO and CH_4 to occur via reaction cycles C1 and C2, the globally averaged, vertical column integrated photochemical production of ozone in the troposphere would be much larger ($\sim5\times10^{11}$ molecules/cm^2/s) than can be balanced by destruction at the earth's surface ($\sim6\times10^{10}$ molecules/cm^2/s) and by photochemical removal via the reactions

R12 $O_3 + h\nu \rightarrow \mathbf{O(^1D) + O_2}$

R13 $O(^1D) + H_2O \rightarrow 2\,OH$

which is estimated at 8×10^{10} molecules/cm^2/s (28, 29). Reactions R12 and R13 constitute the main pathway for the production of hydroxyl radicals (OH), which initiate many oxidation processes in the atmosphere.

BOX 3

Reaction Cycle C4. Atmospheric oxidation of ethane forms ozone as follows. The carbon monoxide (CO) produced may also be oxidized to form additional ozone via cycle C1.

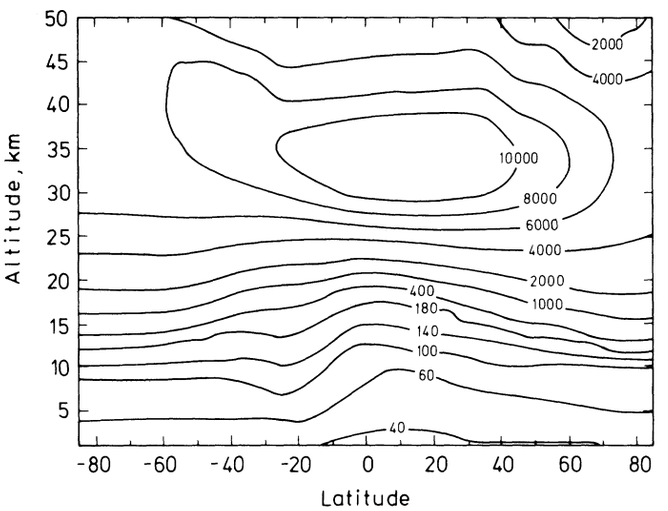
R14 $C_2H_6 + OH \rightarrow C_2H_5 + H_2O$
R15 $C_2H_5 + O_2 + M \rightarrow C_2H_5O_2 + M$
R16 $C_2H_5O_2 + NO \rightarrow C_2H_5O + NO_2$
R17 $C_2H_5O + O_2 \rightarrow CH_3CHO + HO_2$
R18 $CH_3CHO + OH \rightarrow CH_3(C{=}O) + H_2O$
R19 $CH_3(C{=}O) + O_2 + M \rightarrow CH_3(C{=}O)O_2 + M$
R20 $CH_3(C{=}O)O_2 + NO_2 + M \rightarrow CH_3(C{=}O)O_2NO_2 + M$
R21 $CH_3(C{=}O)O_2 + NO \rightarrow CH_3 + CO_2 + NO_2$
R7 $CH_3 + O_2 + M \rightarrow CH_3O_2 + M$
R8 $CH_3O_2 + NO \rightarrow CH_3O + NO_2$
R9 $CH_3O + O_2 \rightarrow CH_2O + HO_2$
R3 $HO_2 + NO \rightarrow OH + NO_2$ (2 times)
R4 $NO_2 + h\nu \rightarrow NO + O$ (5 times)
R5 $O + O_2 + M \rightarrow O_3 + M$ (5 times)
R10 $CH_2O + h\nu \rightarrow CO + H_2$

C5 $C_2H_6 + 10\,O_2 \rightarrow 2\,H_2O + H_2 + CO_2 + CO + 5\,O_3$

The photochemistry of the ethane and higher hydrocarbon oxidation in the atmosphere follows similar reaction paths as for methane, although reactions occur faster because of the higher reactivity of these molecules (27, 30). In the case of ethane, there can be a net production of five ozone molecules per ethane molecule consumed, if sufficient NO is present in the atmosphere. The cycle of reactions, cycle C4, that produces ozone from ethane is shown in Box 3. The compound peroxyacetylnitrate, $CH_3(C{=}O)O_2NO_2$, which appears in C4 is a strong phytotoxicant and air pollutant, better known by the acronym PAN (31). The compound, CH_2O, is formaldehyde and CH_3CHO is acetaldehyde.

Few observations of NO in the background atmosphere have been made, mainly due to the extreme difficulties which are involved in its measurement at low concentrations (32, 33). The hypothesis that ozone production may take place only in a relatively small fraction of the troposphere is in accordance with present estimations of the sources and sinks of tropospheric NO_x (34). According to this compilation, the tropospheric sources of NO_x are dominated by industrial activities. This could imply that the current concentrations of tropospheric ozone in the Northern Hemisphere are substantially larger than those which prevailed during pre-industrial times.

Figure 1. Ozone mixing ratios (ppbv, 1 ppbv = 10^{-9}) in the present atmosphere as calculated by the 2-D model for August 1.



We have modeled the atmospheric photochemistry following a Scenario I nuclear war under the illustrative assumptions listed above. A description of the computer model used in this work is provided in Appendix II. The mixing ratios of ozone in the present atmosphere as calculated by the unperturbed model for August 1 are provided in Figure 1, and these are in good agreement with the observations (35). The calculated ozone concentrations on August 1, 50 days after the start of the war, are shown in Figure 2. We notice the possibility of severe world-wide smog conditions resulting in high concentrations of ozone. With time, at midlatitudes in the Northern Hemisphere there may be large accumulations of ethane (50–100 ppbv) and PAN (1–10 ppbv).

EFFECTS OF TROPOSPHERIC COMPOSITION CHANGES

For Ambio's Scenario I type of war the most significant effects in the atmosphere will occur as a result of the wide variety of large fires, which affect especially military, urban and industrial centers, agricultural fields, oil and gas production areas, and forests. In the preceding section, we have considered a scenario of events which, in our opinion, represents probably the minimum of what may occur: wildfires in 10^6 km^2 of forests, and the burning and escape of oil and natural gas at rates comparable to present industrial usage. The estimated atmospheric effects are very large. The fires would create sufficient quantities of airborne particulate matter in the atmosphere to screen out a large fraction of the solar radiation for many weeks, strongly reducing or even eliminating the possibility of growing agricultural crops over large areas of the Northern Hemisphere. Dark aerosol deposits on the vegetation would likewise severely limit plant productivity. In addition, if the war should start during the summer months, as envisaged in the war scenario of this study, much cropland would be destroyed directly by fast-moving fires. Also of special concern are the heavy deposits of air pollutants from the atmosphere which would take place in the months during and following the war. If an appreciable fraction of the NO_x formed in the nuclear explosions and in the resulting fires were to be deposited in rain, the rainwater would be highly acidic with an average pH of less than 4.

If the production of aerosol by fires is large enough to cause reductions in the penetration of sunlight to ground level by a factor of a hundred, which would be quite possible in the event of an all-out nuclear war, most of the phytoplankton and herbivorous zooplankton in more than half of the Northern Hemisphere oceans would die (36). This effect is due to the fast consumption rate of phytoplankton by zooplankton in the oceans. The effects of a darkening of such a magnitude have been discussed recently in connection with the probable occurrence of such an event as a result of the impact of a large extraterrestrial body with the earth (37). This event is believed by many to have caused the widespread and massive extinctions which took place at the Cretacious-Tertiary boundary about 65 million years ago.

For several weeks following the war the physical properties of the Northern Hemispheric troposphere would be fundamentally altered, with most solar energy input being absorbed in the atmosphere instead of at the ground. The normal dynamic and temperature structure of the atmosphere would therefore change considerably over a large fraction of the Northern Hemisphere, which will probably lead to important changes in land surface temperatures and wind systems. The thick, dark aerosol layer would likely give rise to very stable conditions in the troposphere (below 10 km) which would restrict the removal of the many fire-produced and unhealthy pollutants from the atmosphere. Furthermore, fires also produce as many as $6{\times}10^{10}$ cloud condensation nuclei per gram of wood consumed. The effect of many condensation nuclei is to narrow the cloud droplet size distribution and suppress formation of rain droplets by coalescence, probably leading to a decrease in the efficiency with which clouds can produce rain (38). The influence of large-scale vegetation fires on weather has been recognized by researchers for many years (*eg* 39). After the settling of most of the particulate matter, ozone concentrations over much of the Northern Hemisphere could approach 160 ppbv for some months fol-

lowing the war. With time, substantial increases in other pollutants such as PAN to several ppbv may also occur. These species are important air pollutants which are normally present in the atmosphere at much lower concentrations (~30 ppbv for ozone and less than 0.1 ppbv for PAN) (33, 40, 41).

The effects of ozone on public health and plant growth have been studied for several decades, especially in the US in connection with the Los Angeles basin photochemical smog problem. The effects on agricultural plants may be particularly severe. A major EPA report (31), listed several examples of decreases in yields of agricultural crops. For instance: "A 30 percent reduction in the yield of wheat occurred when wheat at antheses [blooming] was exposed to ozone at 200 ppbv, 4 hours a day for 7 days... Chronic exposures to ozone at 50–150 ppbv for 4–6 hours a day reduced yields in soybeans and corn grown under field conditions. The threshold for measurable effects for ozone appear to be between 50 and 100 ppbv for sensitive plant cultivers... An ozone concentration of 50 to 70 ppbv for 4 to 6 hours per day for 15 to 133 days can significantly inhibit plant growth and yield of certain species."

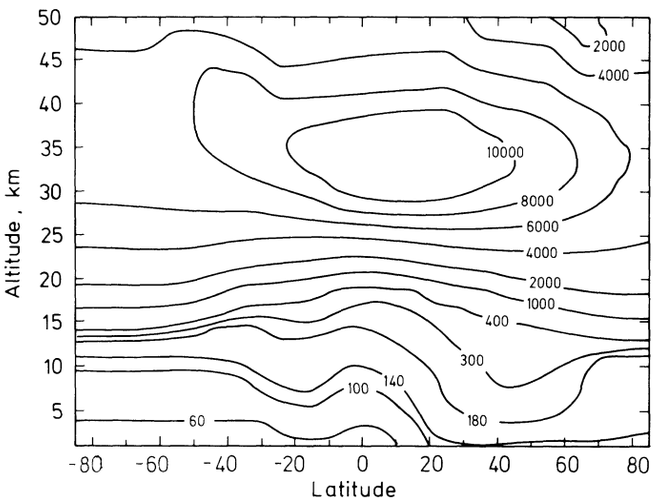
As a result of the nuclear holocaust we have indicated the possibility of an increase of average ground level ozone concentration to 160 ppbv with higher values to be expected in areas in the wake of the mix of forest and gas and oil well fires assumed in this study. It follows, therefore, that agricultural crops may become subjected to severe photochemical pollutant stress in addition to the even greater damaging effects due to the large load of aerosol particles in the atmosphere.

We conclude, therefore, that the atmospheric effects of the many fires started by the nuclear war would be severe. For the war scenario adopted in this study, it appears highly unlikely that agricultural crop yield would be sufficient to feed more than a small part of the remaining population, so many of the survivors of the initial effects of the nuclear war would probably die of starvation during the first post-war years. This analysis does not address the additional complicating adverse effects of radioactivity or synergism due to concomitant use of chemical and biological warfare weapons.

The described impacts will be different if a nuclear war starts in the winter months. Forest areas burned may be half as large (7), photochemical reactions would be slower because of less solar radiation and lower temperatures. However, in wintertime, because of the low sun, the darkness caused by the fire-produced aerosol would be much worse.

In this work little discussion could be devoted to the health effects of fire-produced pollutants. They too, no doubt, will be more serious in winter than in summer.

Figure 2. Ozone mixing ratios (ppbv) on August 1, 50 days after the beginning of the Scenario I nuclear war. Inputs from forest fires and oil and gas well fires as described in the text.



STRATOSPHERIC OZONE DEPLETION

In the stratosphere, molecular oxygen, O_2, absorbs solar radiation of wavelengths shorter than 242 nm and dissociates into two oxygen atoms. These oxygen atoms combine with two oxygen molecules to form two ozone molecules as follows:

R14 $O_2 + h\nu \rightarrow O + O$

R5 $O + O_2 + M \rightarrow O_3 + M$ **(Twice)**

This formation mechanism is quite different from that described previously for the troposphere and summarized in cycles C1 and C2 of Box 2. Whereas oxides of nitrogen promote ozone formation in the troposphere, in the stratosphere, where the chemical composition and light spectrum are quite different, the effect of oxides of nitrogen is to catalyze ozone destruction via the reactions:

R15 $NO + O_3 \rightarrow NO_2 + O_2$

R16 $O + NO_2 \rightarrow NO + O_2$

R17 $O_3 + h\nu \rightarrow O_2 + O$

Net: $2\,O_3 \rightarrow 3\,O_2$

It is now recognized that this cycle is the principal means by which ozone is limited in the natural stratosphere (42). Also, whereas ozone is an undesirable pollutant in the troposphere, in the stratosphere ozone performs the necessary function of shielding the earth's surface from biologically damaging ultraviolet radiation.

Our model does not predict significant stratospheric ozone depletion for Ambio's reference Scenario I since as seen in Table 1, very little NO_x is deposited in the stratosphere for this scenario. However, for Scenario II (based on previous studies)—which considers the detonation of numerous weapons of large yield—the model predicts very large depletions. For this scenario the quantity of NO_x in the stratosphere of the Nothern Hemisphere is increased by a factor of approximately twenty above the natural level (21). The resulting large ozone depletions would begin in the Northern Hemisphere and eventually spread to the Southern Hemisphere. For purposes of illustration, the Scenario II nuclear war begins on June 11. The resulting ozone depletions on November 1 of the same year are shown in Figure 3. These large ozone depletions are consistent with the one-dimensional model results of Whitten, Borucki and Turco (2) and with the result of Chang as reported by the US National Academy of Sciences (1).

Whitten *et al* (2) considered total bomb yields in the range of 5000–10 000 Mt. They distributed the weapon yields either equally between 1-Mt and 5-Mt weapons or equally between 1-Mt and 3-Mt weapons. They also considered that the NO_x was either uniformly distributed throughout the Northern Hemisphere or spread uniformly between 30° and 70° N. Maximum depletion of the ozone column occurred two to three months following the NO_x injection and ranged from 35–70

percent. The 35 percent depletion occurred for the 5000 Mt total yield distributed equally between 1-Mt and 3-Mt bombs and spread uniformly over the entire Northern Hemisphere. The maximum of 70 percent depletion occurred for a total bomb yield of 10 000 Mt distributed equally between 1-Mt and 5-Mt explosions and confined to the region 30°–70° N. The time constant (e-folding time) for ozone recovery was approximately three years.

The NAS report (1) reaches similar conclusions. A 10 000 Mt war, confined to the Northern Hemisphere, is projected to result in a 30–70 percent ozone column reduction in the Northern Hemisphere and a 20–40 percent reduction in the Southern Hemisphere. Again, the characteristic recovery time was found to be approximately three years. Within ten years the ozone column depletions were estimated to have decreased to 1–2 percent.

Our two-dimensional model predicts a rather uniform 65 percent depletion of the ozone column spread from 45° N to the North Pole by the 50th day following the war. The depletions become less toward the equator and beyond, being 57, 42, 26, 12 and 1 percent at 35° N, 25° N, 15° N, 5° N and 5° S, respectively. As time progresses, the ozone depletions become less in the Northern Hemisphere, but NO_x is transported to the Southern Hemisphere and causes significant depletion there. Two years following the war in the Northern Hemisphere the ozone column depletions vary uniformly from 15 percent at 5° N to 56 percent at 85° N, with a 39 percent depletion of the ozone column at 45° N. At the same time ozone column depletions range from 12 percent at 5° S to 18 percent at 85° S in the Southern Hemisphere.

An important uncertainty in the model calculations for the stratosphere stems from the perturbations in the heating rates that accompany the large ozone depletions. Reduction of ozone causes a cooling of the stratosphere. By absorbing ultraviolet sunlight, ozone heats the atmosphere and causes the temperature inversion that is responsible for the high degree of resistance to vertical mixing. To a large extent the NO_x is partitioned into NO_2 in the stratosphere, and the absorption of solar radiation by this species also heats the stratosphere. We find that the net effect at midlatitudes in the perturbed stratosphere is heating below about 22 km and cooling above. The net heating below 22 km is due both to greater penetration of solar uv as a result of the reduced ozone column and the added heating in this region due to NO_2. This will undoubtedly affect the dynamics of the stratosphere and the temperature profile in the stratosphere in complex ways which we cannot predict. We can be confident, however, that the perturbation in the ozone column would be quite large for a Scenario II nuclear war.

Finally, we may point out that there is a possibility that even a nuclear war according to Scenario I, in which most NO_x is deposited in the troposphere, may cause ozone depletions in the stratosphere, if the hot fires in the oil and gas production regions become so powerful that the fire plumes penetrate into the stratosphere. Another means of upward transport may occur when the heavy, dark aerosol layer, initially located in the troposphere, is heated by solar radiation and starts to set up convection and wind systems which will transport an appreciable fraction of the fire effluents into the stratosphere. These speculative thoughts may be pursued further with currently available general circulation models of the atmosphere.

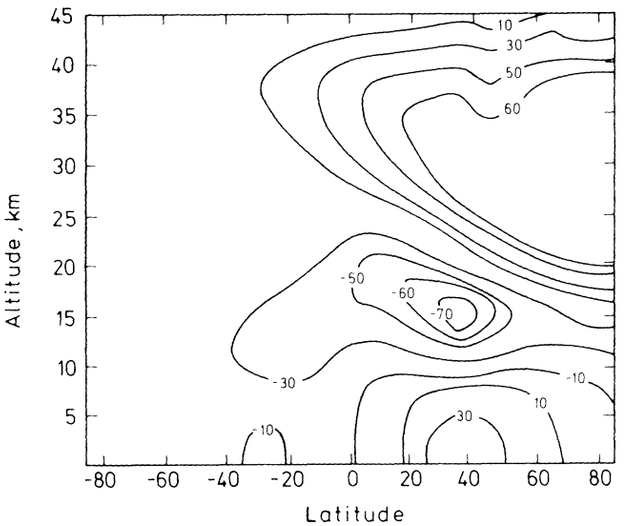


Figure 3. Atmospheric ozone depletion (%) on August 1 of the same year as the Scenario II nuclear war. Negative values indicate ozone increases and show the opposite effects of NO_x injections on ozone in the upper and lower regions of the atmosphere.

Past Nuclear Weapons Tests

In light of this discussion, one might naturally ask whether past nuclear weapon testing in the atmosphere resulted in significant ozone depletion. This topic has been the subject of considerable debate (43–52). That nuclear explosions produce copious quantities of nitric oxide and that multi-megaton bursts deposit this NO in the stratosphere was first recognized by Foley and Ruderman (44). The problem was presented as a possible test of whether NO_x from SST airplane exhaust would actually damage the ozone layer as suggested by Johnston (53) and Crutzen (54). The approximately 300 Mt of total bomb yield in a number of atmospheric tests by the US and USSR in 1961 and 1962 introduced about 3×10^{34} additional molecules of NO to the stratosphere. Using a one-dimensional model, Chang, Duewer and Wuebbles (49) estimated that nuclear weapon testing resulted in a maximum ozone depletion in the Northern Hemisphere of about 4 percent in 1963. Analysis of the ground ozone observational data for the Northern Hemisphere by Johnston, Whitten and Birks (45) revealed a decrease of 2.2 percent for 1960–1962 followed by an increase of 4.4 percent in 1963–1970. These data are consistent with the magnitude of ozone depletion expected, but by no means is a cause-and-effect relationship established. Angell and Korshover attribute these ozone column changes to meteorological factors (47, 48). The ozone increase began before most of the large weapons had been detonated and persisted for too long a period to be totally attributed to recovery from bomb-induced ozone depletion. Considering the large scatter in ozone measurements and our lack of understanding of all of the natural causes of ozone fluctuations, we cannot draw definite conclusions based on ground observations of ozone following the nuclear weapons tests of the late 1950's and early 1960's.

Solar Proton Events

From the previous discussion it is clear that we have no direct experimental evidence for stratospheric ozone depletion as a result of nuclear explosions. However, at least for altitudes above 30 km the sudden input of significant amounts of NO_x has clearly been shown to lead to large ozone destructions. In August 1972 a major solar proton event deposited large amounts of nitrogen oxides in the stratosphere, leading to ozone depletions poleward of about 60° N. The estimated ozone depletions calculated with a photochemical model were confirmed by satellite observations of stratospheric ozone (55).

EFFECTS OF INCREASED UV-B RADIATION

Ozone in the stratosphere serves as a protective shield against the harmful effects of solar radiation in the wavelength region 240–320 nm (10^{-9} meter). The flux of radiation in the wavelength region 290–320 nm ("uv-B" radiation) is particularly

sensitive to very small changes in the ozone column (1). This biologically active radiation is also absorbed by the proteins and nucleic acids within living cells, resulting in a large variety of photoreactions and consequent cell damage (56–58).

The expected adverse effects of increased levels of uv-B radiation include increased incidence of skin cancer in fair-skinned races, decreased crop yields and a variety of stresses on terrestrial and aquatic ecosystems. Such effects have been considered in the past in connection with possible reduction of the ozone shield by the operation of fleets of SST airplanes (59) and by the continued release of chlorofluoromethanes used as refrigerants and as propellants in aerosol spray cans (60). The information available is insufficient to allow quantification of most of these effects. Epidemiological data were used in the NAS study (1) to estimate that a 50 percent ozone shield reduction lasting three years would lead to an increase of skin carcinoma and melanoma of 3 percent to 30 percent at midlatitudes, with a geometric mean of about 10 percent, that will persist for 40 years. This may be compared with the estimate made in the same study that during the first generation a 10 000 Mt war would increase the spontaneous cancer death rate by about 2 percent as a result of exposure to low levels of ionizing radiation from radioactive fallout.

Effects of increased uv-B radiation on food crops are extremely difficult to predict. The sensitivity of plants to supplemented uv-B has been found to be highly variable from one species to another. For example, whereas peas and onions are sensitive, more important food crops such as soybeans and corn appear to have a higher tolerance (1). Possible climatic changes following a nuclear war further complicate the picture for food crops. Crops are particularly sensitive to temperature, length of growing season and amount of precipitation. The coupling of significant changes in one or all of these factors with a change in the spectrum and intensity of light reaching the earth's surface could be particularly detrimental.

Reduction in stratospheric ozone and the concomitant increase in uv-B radiation would also stress natural ecosystems. As in agriculture, individual species of plants and animals differ considerably in their sensitivities to uv-B radiation. However, in natural ecosystems a direct effect on only one species may be propagated to a large number of species because of complex interdependences. For example, the food chain of the oceans is based on photosynthesis by phytoplankton, and these microscopic, green plants have been demonstrated to be quite sensitive to uv radiation (60). It was estimated from uv-B irradiation experiments that a 16 percent ozone reduction (the degree of ozone depletion projected by the NAS study for continued release of chlorofluoromethanes) could kill up to 50 percent of the anchovies in the top 10 meters of the clearest ocean water or else require them to substantially deepen their usual water depth (60, 61). Avoidance could provide protection for many animals, but it is thought that few species can sense uv-B light.

The "effective" increases in uv-B radiation may be determined by integrating the product of the uv-B radiation flux and the appropriate "action spectrum" over wavelength. We have computed these integrals using the action spectrum for erythema (sunburn). This action spectrum is very similar to the absorption spectrum of DNA, as are most uv-B action spectra, and thus the results apply rather generally to cell damage of all types (62). The relative increases in effective uv-B radiation are shown in Figure 4 for several latitudes as a function of time following the nuclear war. As noted earlier, the uv-B increases are extremely large and persist for several years. The Scenario II nuclear war initially would result in increases in uv-B radiation by a factor greater than 5 throughout most of the Northern Hemisphere and greater than 10 between 55° N and the North Pole. These large increases in uv-B radiation are expected to persist long after the attenuation of light by atmospheric aerosol produced by the nuclear blasts and by the many fires is no longer significant. By comparison, the projected increase in effective uv-B radiation for continued release of chlorofluoromethanes at 1977 levels is 44 percent (60).

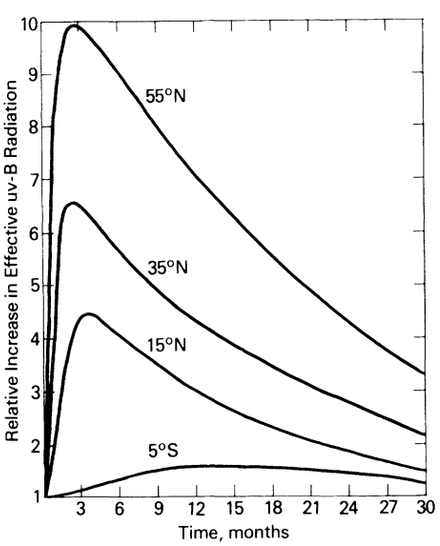


Figure 4. Relative increases in effective uv-B radiation based on the erythema action spectrum for the Scenario II nuclear war.

LONG-TERM EFFECTS

Regarding possible climatic effects, little can be said with confidence. The increase in tropospheric ozone, methane and possibly other pollutant gases may lead to increased temperatures at the earth's surface (63, 64), while the dark aerosol produced by the fires will change the heat and radiative balance and dynamics of the earth and the atmosphere for awhile. Longer lasting effects may be caused by the changes in the reflective properties of the land surfaces because of many fires. In a recent study Hansen *et al* (65) have been able to trace observed mean global temperatures over the past 100 years with a simple climate model by introducing changes in the atmospheric CO_2 content, volcanic activity and solar variability as the main driving forces. In their model the climate sensitivity was also tested for various global radiation perturbations which are relevant for this study: stratospheric aerosol, tropospheric aerosol (divided into opposite sulfate and soot effects), and atmospheric trace gas content (carbon dioxide, ozone, methane and nitrous oxide). From this study it is conceivable that climate could be sensitive over the short term to the tropospheric and stratospheric aerosol loading. It may be possible to test the impact of a nuclear war on climate with this and similar models, when these are supplied with reasonable estimates of the trace gas and aerosol composition of the earth's atmosphere. Whether the induced perturbation in the climate system could lead to longer lasting climatic changes will, however, be difficult to predict. In fact, it may seem unlikely that it will take place. The Krakatoa volcanic eruption of 1883 injected quantities of aerosol into the atmosphere comparable to those which would be caused by a nuclear war, and global mean temperatures were affected for only a few years (1). Still, we must be cautious with a prediction as the physical characteristics of the aerosol produced by volcanos and fires are different, and much is still unknown about the fundamentals of climatic changes. For instance, we may ask questions such as whether the earth's albedo would be substantially altered after a nuclear war and thus affect the radiation balance or whether the deposition of soot aerosol on arctic snow and ice and on the glaciers of the Northern Hemisphere might not lead to such heavy snow and ice melting as to cause an irreversible change in one or more important climatic parameters.

CONCLUSIONS

In this study we have shown that the atmosphere would most likely be highly perturbed by a nuclear war. We especially draw attention to the effects of the large quantities of highly sunlight-absorbing, dark particulate matter which would be produced and spread in the troposphere by the many fires that would start burning in

urban and industrial areas, oil and gas producing fields, agricultural lands, and forests. For extended periods of time, maybe months, such fires would strongly restrict the penetration of sunlight to the earth's surface and change the physical properties of the earth's atmosphere. The marine ecosystems are probably particularly sensitive to prolonged periods of darkness. Under such conditions it is likely that agricultural production in the Northern Hemisphere would be almost totally eliminated, so that no food would be available for the survivors of the initial effects of the war. It is also quite possible that severe, worldwide photochemical smog conditions would develop with high levels of tropospheric ozone that would likewise interfere severely with plant productivity. Survival becomes even more difficult if stratospheric ozone depletions also take place. It is, therefore, difficult to see how much more than a small fraction of the initial survivors of a nuclear war in the middle and high latitude regions of the Northern Hemisphere could escape famine and disease during the following year.

In this paper we have attempted to identify the most important changes that would occur in the atmosphere as a result of a nuclear war. The atmospheric effects that we have identified are quite complex and difficult to model. It is hoped, however, that this study will provide an introduction to a more thorough analysis of this important problem.

APPENDIX I

Production and Spatial Distribution of Nitric Oxide From Nuclear Explosions

There have been numerous estimates (43–46, 66) of the yield of nitric oxide per megaton (Mt) of explosion energy, and these have been reviewed by Gilmore (66). Nitric oxide is produced by heating and subsequent cooling of air in the interior of the fireball and in the shock wave.

The spherical shock wave produces nitric oxide by heating air to temperatures above 2200 K. This air is subsequently cooled by rapid expansion and radiative emission, while the shock front moves out to heat more air. At a particular temperature the cooling rate becomes faster than the characteristic time constant for maintaining equilibrium between NO and air. For cooling times of seconds to milliseconds the NO concentration "freezes" at temperatures between 1700 and 2500 K, corresponding to NO concentrations of 0.3–2 percent. Gilmore (66) estimates a yield of 0.8×10^{32} NO molecules per Mt for this mechanism.

The shock wave calculation of NO production does not take into account the fact that air within the fireball center contains approximately one-sixth of the initial explosion energy, having been heated by the radiative growth mechanism described earlier. This air cools on a time scale of several seconds by further radiative emission, entrainment of cold air, and by expansion as it rises to higher altitudes. These mechanisms are sufficiently complex that one can only estimate upper and lower limits to the quantity of NO finally produced.

A lower limit to total amount of NO finally produced may be obtained by assuming that all of the shock-heated air is entrained into the fireball and again heated to a high enough temperature to reach equilibrium. This is possible since the thickness of the shell of shock-heated air containing NO is smaller than the radius of the fireball. To minimize the cooling rate, and thus the temperature at which equilibrium is not re-established rapidly, it is assumed that this air mass cools only by adiabatic expansion as the fireball rises and by using a minimum rise velocity. The resulting lower limit to total NO production is 0.4×10^{32} molecules per Mt (66).

Since the interior of the fireball is much hotter than the surrounding, shock-heated air, it will rise much faster and possibly pierce through the shell of shock-heated air to mix with cold, undisturbed air above it. Thus, an upper limit to NO production may be obtained by assuming that none of the 0.8×10^{32} NO molecules per Mt produced in the shock wave are entrained by the hot fireball interior. Instead, one assumes that the interior is cooled totally by entrainment of cold, undisturbed air to produce additional NO. The upper limit to total NO production is then estimated to be 1.5×10^{32} molecules per Mt (66). Thus, the range of uncertainty for total NO_x formation is $0.4–1.5\times10^{32}$ molecules per Mt.

For the purposes of this study we assume a nitric oxide yield of 1.0×10^{32} molecules per Mt. One can make strong arguments against either of the extreme values. This estimate of NO production applies only to detonations in the lower atmosphere.

In a nuclear war some bombs may be exploded at very high altitudes for the purpose of disrupting radio and radar signals. The ionization of air by gamma rays, X-rays and charged particles creates a phenomenon known as the "electromagnetic pulse" or "EMP" (67). The partitioning of energy between the locally heated fireball, shock wave, and escaping thermal radiation changes dramatically as the altitude of the explosion increases above 30 km. As the altitude increases, the X-rays are able to penetrate to greater distances in the low density air and thus create very large visible fireballs. For explosions above about 80 km, the interaction of the highly ionized weapon debris becomes the dominant mechanism for producing a fireball, and for such explosions the earth's magnetic field will influence the distribution of the late-time fireball. Explosions above 100 km produce no local fireball at all. Because of the very low air density, one-half of the X-rays are lost to space, and the one-half directed toward the earth deposits its energy in the so-called "X-ray pancake" region as they are absorbed by air of increasing density. The X-ray pancake is more like the frustum of a cone pointing upward, with a thickness of about 10 km and a mean altitude of 80 km. The mean vertical position is essentially independent of the explosion altitude for bursts well above 80 km (67).

The absorption of X-rays by air results in the formation of pairs of electrons and positively charged ions. One ion pair is formed for each 35 eV of energy absorbed (68), and in the subsequent reactions approximately 1.3 molecules of NO are produced for each ion pair (69). A 1-Mt explosion corresponds to 2.6×10^{34} eV of total energy. Thus, considering that only half of the X-rays enter the earth's atmosphere, the yield of NO is calculated to be 4.6×10^{32} molecules per Mt (*ie* this mechanism is about five times more effective at producing NO than the thermal mechanism described above).

In the course of a nuclear war up to one hundred 1-Mt bombs might be detonated in the upper atmosphere for the purpose of creating radio wave disturbances. The injection of NO would therefore be 4.8×10^{34} molecules or 1.1 Tg of nitrogen. Natural production of NO in the thermosphere due to the absorption of EUV radiation depends on solar activity and is in the range 200–400 Tg of nitrogen per year (34). Thus the amount of NO injected by such high altitude explosions is about equal to the amount of NO produced naturally in one day and falls within the daily variability. In addition, the X-ray pancake is positioned at an altitude where nitrogen and oxygen species are maintained in photochemical equilibrium. Excess nitric oxide is rapidly destroyed by a sequence of reactions involving nitrogen and oxygen atoms as follows:

$$\begin{aligned} &\text{R22} \quad NO + h\nu \rightarrow N + O \\ &\text{R23} \quad N + NO \rightarrow N_2 + O \\ &\text{Net:} \quad 2\,NO \rightarrow N_2 + O + O \rightarrow N_2 + O_2 \end{aligned}$$

For these reasons, we expect that high altitude explosions of such magnitudes will have no significant global effect on the chemistry of the stratosphere and below.

Results of past tests of nuclear explosions show that nuclear clouds rise in the atmosphere and finally stabilize at altitudes that scale approximately as the 0.2 power of bomb yield. An empirical fit to observed cloud geometries at midlatitudes gives the following expressions for the heights of the cloud tops and cloud bottoms, respectively (44):

$$H_T = 22Y^{0.2}$$
$$H_B = 13Y^{0.2}$$

where H is in kilometers and Y has units of megatons. Thus, bomb clouds from weapons having yields greater than about 1 Mt completely penetrate the tropopause at midlatitudes. For such explosions all of the NO_x produced in the fireball, and perhaps a significant fraction of that produced in the shock wave but not entrained by the bomb cloud, is deposited in the stratosphere. Oxides of nitrogen formed in nuclear explosions having yields less than 1 Mt have little effect on stratospheric ozone since: 1) only a minor fraction of the NO_x formed is deposited above the tropopause, 2) the residence time in the stratosphere increases with altitude of injection, and 3) the NO_x-catalytic cycle for ozone destruction is most effective at higher altitudes. In fact, below about 20 km NO_x additions to the atmosphere tend to result in ozone concentration increases (70, 71).

The stabilized nuclear bomb clouds have diameters ranging from 50 to 500 km depending on bomb yield. They are sheared by horizontal winds at constant latitude, and within a few weeks may be uniformly distributed around the earth at a constant latitude (72).

APPENDIX II

Model Description

The computer model used in this study is a two-dimensional model of coupled photochemistry and dynamics. It treats transport in both the vertical and latitudinal directions by parameterization of these motions by means of eddy diffusion coefficients and mean motions. The model covers altitudes between the ground and 55 km and latitudes between the South Pole and North Pole, and it attempts to simulate the longitudinally averaged, meridional distributions of trace gases. Therefore, the main assumption is that composition variations in the zonal (East–West) directions are much smaller than those in the vertical and latitudinal directions. Although the 2-D model is a step forward from 1-D models, which take into account only variations in the vertical direction, the neglect of longitudinal variations in air composition will clearly introduce substantial deviations from reality, especially at lower altitudes, where the influence of chemical and biological processes at the earth's surface are large. One should keep these limitations of the 2-D model in mind especially when interpreting the results obtained for the troposphere.

The model photochemistry considers the occurrence of nearly one hundred reactions, which are now thought to be important in global air chemistry. It takes into account the reactions of ozone and atomic oxygen, and the reactive oxides of nitrogen, hydrogen and chlorine, which are derived from the oxidation of nitrous oxide (N_2O), water vapor (H_2O), methane (CH_4) and organic chlorine compounds. In the troposphere, the photochemistry of simple reactions leading to ozone formation in the presence of NO_x, carbon monoxide (CO), methane and ethane (C_2H_6) are taken into account. The influence of industrial processes is an important consideration of the model. A more detailed description of the model may be found elsewhere (71, 72). Detailed descriptions of atmospheric photochemistry are given in a number of review articles (34, 73–75).

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