Nuclear winter: A matter of degrees

The major climatic effects from nuclear war would come from soot generated by urban fires; much research will be needed to clarify the uncertainties.

Barbara G. Levi and Tony Rothman

Although climatic impacts have long been on the list of potential consequences of nuclear war, two years ago they were predicted to be so devastating as to earn the label, "nuclear winter." That term describes a world that is plunged into cold and darkness because the sunlight is blocked by smoke from fires ignited by nuclear explosions and by the dust from nuclear groundbursts. This vision is considerably more severe than any painted earlier because the calculations for the first time included massive injections of soot, the carbonaceous component of smoke. The soot strongly absorbs the incoming sunlight but transmits most of the outgoing infrared radiation, creating an inverse greenhouse effect.

The dramatic prediction of nuclear winter naturally caught the public spotlight. It reinforced calls for sharp arms reductions and stimulated debate over possible policy implications. It also spurred review of the predictions by other scientists. The calculations underlying nuclear winter involve a wide variety of disciplines, and the theory rests on numerous assumptions for which the data are sparse or even nonexistent. As a result, the uncertainties in virtually every parameter are wide. The calculations predict such massive injections of smoke and dust into the atmosphere that they greatly challenge atmospheric scientists who are already struggling to model more modest perturbations to the normal climate patterns. Over the past two years, the input assumptions have been scrutinized and the models modified (see figure 1). While no one can yet either prove or disprove that a nuclear winter might result from a large-scale war, it does seem that some climatic impact would occur. Much of the debate now centers on the extent of the cooling and on the magnitude and type of the nuclear exchange that might cause it.

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History of the problem

One of the first questions to be asked about nuclear winter was why no one had predicted it sooner. Actually, although the recent quantitative treatment required a convergence of knowledge from widely different fields, ingredients to this calculation had been at least qualitatively recognized over the years. The first substantial concern over the global atmospheric impacts of nuclear weapons involved the possible effects of the nitrous oxides produced by nuclear explosions on the stratospheric ozone layer that now protects Earth from harmful ultraviolet radiation. One study in the mid 1970s investigated[1] the suggestion that the nuclear fireballs might produce such a large quantity of nitrous oxides that the reactions they catalyze would seriously deplete the ozone layer. In a 1984 study of the climatic effects of nuclear war, the National Academy of Sciences reiterated this concern[2] and cautioned the world to worry not only about nuclear winter but also about "ultraviolet summer."

Another concern over atmospheric impacts has been that the dust from groundbursts might block out the solar radiation and cause Earth to cool. The earliest treatments of dust from nuclear bombs concluded that a single explosion couldn't produce enough dust for a noticeable effect on Earth's climate. However, by the mid 1960s the arsenals were sufficiently large that a massive exchange had become a possibility. The quantity of aerosols potentially raised by a war involving nuclear explosions equivalent to 5000–10 000 Mt of TNT might be comparable to what was spewed out by large volcanic eruptions in the past. Volcanoes are only a weak analogy, but historical evidence of their impact tends to suggest what might result from the dust ejected by a large-scale nuclear war. For example, the 1815 eruption of Tambora in Indonesia drove so many particles into the stratosphere that it apparently affected weather patterns around the globe. Although the annual mean temperature in the Northern Hemisphere for the subsequent year may have dropped[3] by less than one degree Celsius, 1816 was marked by anomalous weather events such as New England snowfalls in June and has been dubbed[4] "the year without summer." It has also been hypothesized[5] that the extinction of the dinosaurs occurred after an asteroid, perhaps 10 km in diameter, struck the Earth and raised a dust cloud that obscured sunlight (see PHYSICS TODAY, May 1982, page 19). (The energy of that asteroid impact would have been ten thousand times that released in a 5000–Mt nu-

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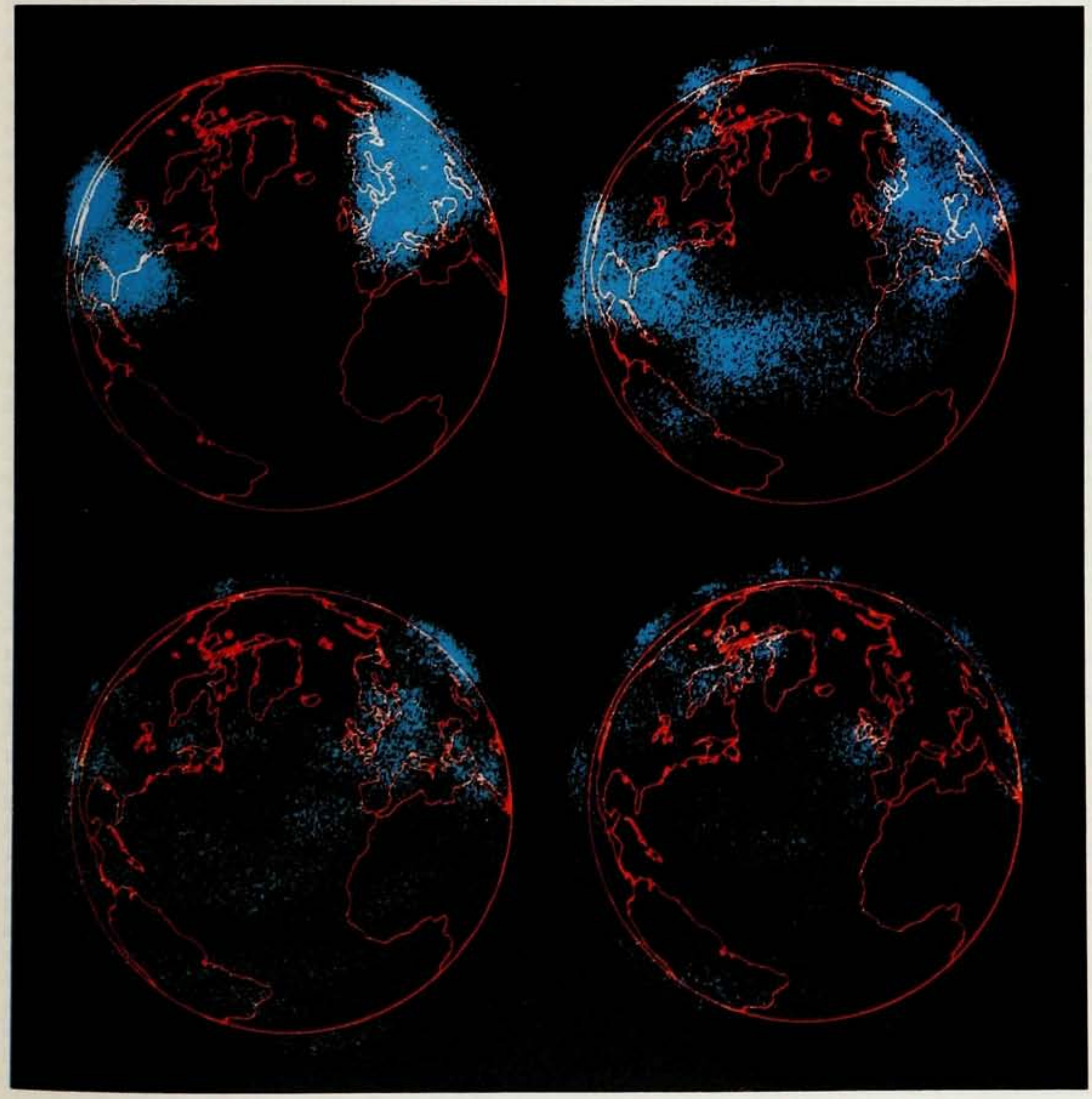
Global smoke distributions. The maps show distributions 1, 5, 10, and 20 days after injections of smoke at five points: two in the US, one in Europe and two in the USSR. A total of 150 Tg of smoke is assumed to be injected; each dot represents 4000 tons of smoke spread throughout a volume of 550 000 km^3. (Lawrence Livermore National Lab.) Figure 1



Convection column established over a 1600-acre, helicopter-ignited prescribed burn near Chapleau, Ontario, 3 August 1985. The burn served to provide information on smoke emissions from fires simulating those created in nuclear explosions; it was carried out in tramped, dead forest fuels to reduce surface fuel loadings and prepare the site for planting. Figure 2

clear war.)

By rough analogy with the Tambora eruption, the dust from a large-scale war might be expected to lower the average yearly northern hemispheric temperatures by about one Celsius degree. The first nuclear-winter calculations, however, estimated far greater temperature drops—with a maximum of about 35 °C. The key element is the soot. A relevant analogy from nature in this case is that of plumes from intense forest fires: In 1950, the smoke pall from a fire in western Canada spread across the continent, lowering the predicted maximum temperatures[6] in Washington, D. C. a few days afterward by an estimated several Celsius degrees. Some early studies of nuclear weapons effects done in the mid 1960s loosely mentioned[7] the possibility that smoke from fires set by nuclear war might severely affect the climate. However, no one treated the effect quantitatively until 1982, when Paul Crutzen and John Birks estimated[8] the solar attenuation that might result if a nuclear war set ablaze one million square kilometers of forest land. They suggested that fires in urban areas, especially in regions where quantities of petroleum are stored, might produce even more smoke (see PHYSICS TODAY, October 1982, page 17).

Predictions of the TTAPS model

The quantitative predictions that first inspired the term "nuclear winter" were done[9] by Richard Turco, Brian Toon, Thomas Ackerman, Jim Pollack and Carl Sagan (see PHYSICS TODAY, February 1984, page 17). Contrary to the acronym TTAPS formed from their names, the group may have sounded reveille to a potentially important climatic effect. They all had backgrounds in analyzing such phenomena as asteroid impacts, volcanic eruptions and Martian dust storms and applied these backgrounds to an analysis of Crutzen and Birks's idea. The TTAPS group took as their baseline a nuclear war involving 5000 Mt. They estimated the quantities, heights of injection, lifetimes and optical properties of both the dust and the smoke, including soot. They assumed the aerosols were instantaneously and uniformly spread over the Northern Hemisphere; and they fed this information into a one-dimensional calculation that simulated the convective and radiative processes within a globally averaged vertical column of the atmosphere. The model necessarily ignored horizontal transport and the buffering effect of the oceans.

Turco and his colleagues predicted that for their baseline scenario the temperature would drop by approximately 30 °C in the first 20 days and would still remain below normal after one year. These temperatures are relevant over land masses of a planet assumed to have no oceans. Based on model calculations with the surface treated as ocean as well as land, the group estimated that the inclusion of the moderating effect of oceans should cause temperature drops in mid-continental regions to be about 30% smaller, and in coastal regions to be 70% smaller.

In another scenario TTAPS considered an attack involving only airbursts so that no dust was generated. In this case, the temperature returns to prewar values more quickly. In still another scenario, where no dust and no smoke is produced, the temperature drops by at most 7 °C but still remains several degrees below normal after 300 days. The temperature over land surfaces for a land-only planet has an average drop of about 3 °C during the first year, in the "dust only" scenario, which seems consistent with an average temperature drop over the Northern Hemisphere, including oceans, of 1 °C. Hence, the smoke causes the severe temperature drops and the dust prolongs the cooling in the TTAPS model. The reason for the difference in the longevity of effect is that the smoke is generally injected by fires into the troposphere, from which it is normally removed within a few weeks, while a significant fraction of the dust is carried by the fireball into the stratosphere, where it may remain for over a year. It must be noted, however, that the conditions of nuclear winter may greatly alter "normal" atmospheric patterns that promote the scavenging of smoke by rain.

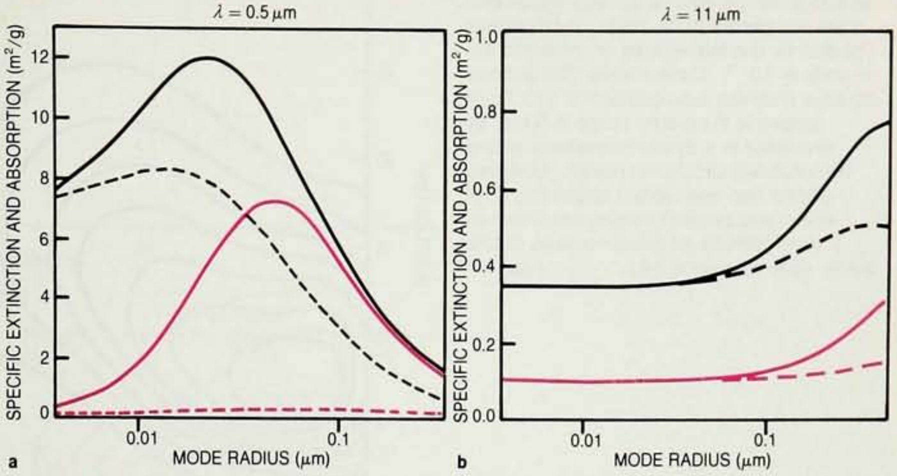
Another TTAPS scenario, termed "100-Mt city attack," deserves special comment, as it is really an excursion from the baseline scenario. Although it involves only 2% of the total yield of the baseline case, this attack produces as sharp a cooling because the very particular circumstances of this scenario create 60% as much smoke as the baseline. This scenario is often cited in debates as evidence that the threshold for the onset of nuclear winter—as

Table 1. TTAPS baseline scenario

Weapon yield (Mt)	Target type	Type of burst	Atmospheric emissions Dust (Tg)	Soot (Tg)
1000	Urban, industrial	Airburst	0	149
4000*	Military	Airburst and groundburst	960*	80
5000		Total	960	229

From reference 9.
*Includes 1150 Mt airburst, which produce the 960 Tg dust.

Specific cross sections for the absorption (dotted lines) and extinction (solid lines) of light by log-normal distributions of smoke (black) and dust (red) particles, at both visible wavelengths (**a**) and long wavelengths (**b**), as a function of their mode radii. For the size range of particles shown, the smoke absorbs visible light far more strongly than infrared, leading to an inverse greenhouse effect. The dust particles largely act to scatter light; much of the sunlight is scattered forward and still reaches the surface. (See reference 19.) Figure 3



measured by the megatons expended—is very low. However, this scenario is not a threshold as measured by its direct consequences on the population: To produce this much smoke with 100 Mt, the bombs must explode only on the built-up centers of cities, where the density of burnable materials is highest. In our analysis we estimate that the area burned in this scenario is equal to approximately 10% of the urban area of about 1000 cities, or virtually all the cities in the more developed countries with populations over 100 000 each[10]—in all, a population of more than 500 million people. Moreover, for this scenario, the TTAPS calculations doubled the parameters assumed for both the fuel loading and for the percentage of urban areas occupied by city centers, and also more than doubled the value assumed for the net smoke emission factor. (They essentially reduced their estimates of the degree of incineration and of the amount of smoke rained out.) Thus they increased the smoke predicted from these urban-center fires by a factor of nearly ten over what they would have calculated using the same parameters as in the baseline scenarios.

The TTAPS estimates of temperature change were reasonably consistent with results from several two- and three-dimensional climate models that appeared at about the same time. All examined the climatic effects of approximately the same, or greater, quantities of soot (see PHYSICS TODAY, March 1984, page 17). Even so, these multidimensional climate models were not fully realistic. Two of the models constrained the soot to a fixed region and calculated the impact on circulation patterns; the third used unperturbed circulation patterns and calculated how the soot might spread. Because they included ocean moderation, these studies generally predicted lower drops than the original TTAPS study. None of the early attempts simulated feedbacks, such as changes in precipitation patterns caused by smoke, which might in turn prolong its residence time in the atmosphere. Some results are beginning to emerge from more interactive models. They have shown that the climatic impact may be far greater for a summer war and that the smoke may be lofted to high altitudes by self-heating. Those working on such models stress[11–14] the complexity of the problem and the (fortunate) absence of real experience against which to test their models in this new regime.

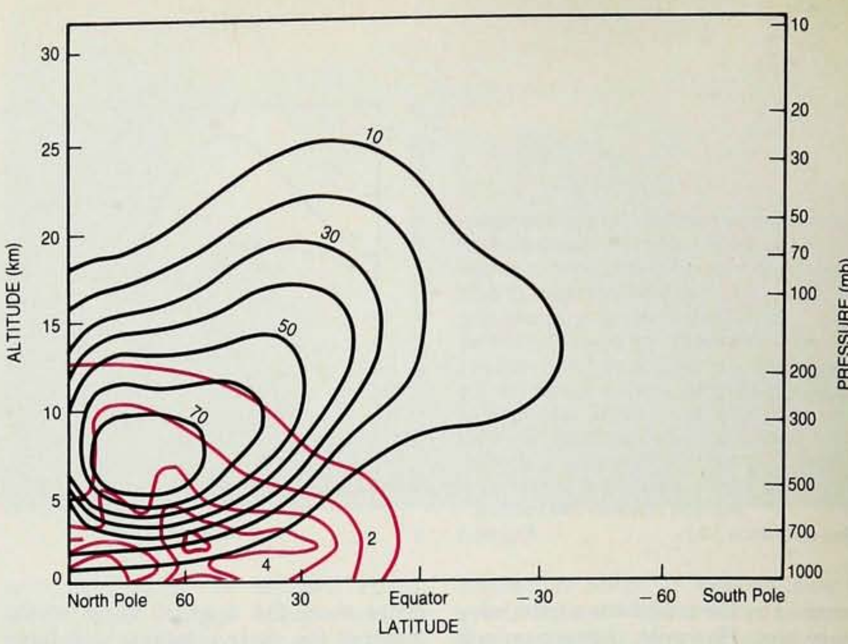
Key questions

The smoke produced in a nuclear exchange is far more instrumental in producing the extreme temperature drops than the dust particles and hence will be the focus of our attention. To estimate how much smoke might be generated requires one to ask many more questions. We begin with the targeting scenario: How many nuclear weapons are aimed at which categories of targets? Table 1 gives the baseline scenario assumed by TTAPS. (A subsequent study by the National Academy of Sciences[2] made similar assumptions.) The total exchange involves 5000 Mt—a significant fraction of the yield in the US and Soviet strategic arsenals and an amount that could conceivably be unleashed in an all-out nuclear war. Just over half of those weapons are assumed to be groundbursts against military targets—presumably against such hardened targets as ICBM silos. About one-fifth of the total yield is assumed to be airbursts on other military targets (such as air bases) and the remaining one-fifth is targeted on urban and industrial targets. Only groundbursts and very low airbursts produce dust; in the model, urban and industrial targets produce about 60% of the total smoke although they account for only 20% of the total yield. Only a fraction of the total 960 Tg of dust estimated to be emitted in this scenario is submicron, stratospheric dust (1 Tg = 10^{12} g).

The quantity of smoke produced by the TTAPS baseline scenario is detailed in table 2. The amount of smoke produced in a fire is the product of: the area burned, the burnable fuel loading (the amount of combustible material per unit area times the fraction of the fuel that actually burns), the fraction of mass that is released as smoke, and the fraction of smoke that is not immediately rained out. Turco and his colleagues assumed that their hypothetical attack would burn 500 000 km^2 of forests and 250 000 km^2 of cities. Although the area of forests assumed to burn was twice that of cities, the fraction of the fuel in forests that actually burns is much lower. The equivalent dry biomass content of forests is about 2 g/cm^2, but typically only a fraction of that is consumed in a fire. The group estimated the burnable fuel loading to be 0.5 g/cm^2. By contrast, in urban areas both the fuel loading and fraction burned would be considerably higher. They estimated that firestorms would develop in the inner 5% of the city area, consuming all the fuel, which they assumed to have an areal density of 10 g/cm^2. The fires in the remaining 95% of the city were taken to burn 50% of the fuel, which has an areal density of 3 g/cm^2. Thus the assumed average fuel loading of material that burns in urban areas corresponds to 1.9 g/cm^2.

In any fire, only a few percent of the fuel by mass is converted to smoke, which is composed partly of soot. Some of the soot may be almost immediately removed in "black rain," which is the rainfall from the cloud that may form over the hot, rising fire plume, as occurred in Hiroshima. Turco and his colleagues assumed that the black rain does not occur at all for forest fires, but

Smoke that absorbs sunlight (black contours) is heated and rises to very high altitudes compared to a passive tracer that does not absorb at all (red). Contours are labeled by the mixing ratio of smoke to air, in units of 10^{-9}. Curves show distributions 20 days after the July injection of 170 Tg of smoke in the height range 2–5 km, as simulated in a three-dimensional global atmospheric circulation model. Because smoke has been lofted above the level where precipitation occurs, ten times as much smoke as tracer remains at this point. (See reference 12.) Figure 4



that rain removes 25% of the soot in urban fires and 50% in firestorms. They further assumed that the smoke emission in firestorms is only half that of general conflagrations, and that in both cases, the percentage of smoke particles less than one micron in radius is 90%. The total mass of smoke particles shown in table 2 is less than the 225 Tg predicted by TTAPS because their model also included a contribution from long-term, or smoldering, fires.

The ranges given in table 3 for the parameter values reflect, in our personal judgment,[15] the current state of knowledge. By comparison, the TTAPS values fall within these ranges, except for their assumptions about forest areas burned. The original TTAPS number was a rough estimate and the area of forest fires continues to be debated. One detailed study estimated[16] that no more than 70 000 km^2 of forests or 190 000 km^2 of vegetation of all types would burn in a 4100-Mt attack on nonurban targets at the most susceptible time of the year. The National Academy study of nuclear winter assumed that 250 000 km^2 of forests might go up in flames if 5000 Mt were targeted outside cities. The discrepancies in the various estimates stem from differing judgments as to the nature of the vegetation surrounding the targets, the susceptibility of the targets to combustion in different seasons (and whether that susceptibility is appreciably different for nuclear explosions), the probability and extent of fire spread and the likelihood that a second burst on the same target would increase the fire-start probability.

Despite the controversy over areas of forests burned, the more critical term in the calculation is the area of urban fires. We have estimated[15] the upper limit for the area of urban fires in table 3 as being equal to the TTAPS value of 240 000 km^2 and close to the National Academy value of 250 000 km^2—but recognize it as a very improbable case. This area corresponds, in the TTAPS baseline scenario, to spacing the 1000 Mt evenly over the areas of virtually every city in the more developed nations having a population exceeding 100 000. An urban area this size might conceivably be burned in a nuclear war, especially if more megatonnage were aimed at cities; however, such an attack would probably require a deliberate policy by both alliances to burn virtually all the adversary's cities.

The lower limit in our range accounts for a possible overlap by a factor of 4 among warheads aimed at targets within the same city. For example, 60 warheads may be targeted[17] at Moscow alone.

Table 3 suggests that fires in outer-city areas are the source of most of the smoke. Current estimates of the urban fuel loadings rely on a few surveys[18] of the "typical" content of American buildings, coupled with assumptions about patterns of building height and density. More data—for Soviet cities as well—would help narrow the uncertainties here. A third factor, smoke emissions, is very difficult to determine for the conditions that might prevail in fires set by nuclear explosions. Current estimates rely either on laboratory-scale fires in controlled conditions or on samples from deliberate burnings of forest material (see figure 2). The range shown in table 3 is the same as that cited by the National Academy study of nuclear winter. The final factor—the percentage of smoke that might be immediately washed out by rain—is also a key factor for which little evidence now exists. The unknowns include the extent to which the soot particles may act as cloud-condensation nucleii.

The net result of all these uncertainties is that estimates of the total amount of smoke resulting from nuclear war vary over a wide range. The National Academy study estimated an "excursion" range from 20–650 Tg about their baseline figure of 180 Tg. To combine the ranges of uncertainties for each parameter given in table 3, we have assumed that all values between the given limits are equally probable. We then computed the mean and standard deviation for the product of these parameters. The amount of smoke could thus vary over a two-standard-deviation range of 4–318 Tg.

The optical properties of smoke greatly differ from those of dust. The dust particles kicked up by nuclear explosions scatter—but only weakly absorb—the incoming sunlight, and much of that scattered light is still directed forward. By contrast, smoke particles strongly absorb and scatter light in the visible region. Both types of particles scatter and absorb infrared radiation weakly. The effective cross section for scattering or absorption by an individual particle is given by the geometric cross section of that particle—πr^2 for a spherical particle—multiplied by the scattering or absorption efficiency Q_{scat} or Q_{abs}. The sum of these two efficiencies is the extinction efficiency. These efficiencies in turn depend on the complex index of refraction, m, of the particle. They indicate how much sunlight is removed from the collimated beam, although some of that light may still reach the ground. The attenuation of sunlight in a unit length of its path

Table 2. Key parameters—TTAPS values

Parameters	Type of region: Forests	Inner city	Outer city	Total
Area burned (1000 km^2)	500	12	228	740
Burnable fuel loading (g/cm^2)	0.5	10	1.5	
Quantity of submicron smoke particles emitted (g/g)	0.032	0.023	0.045	
Fraction of smoke remaining after "black rain"	1.0	0.5	0.75	
Total smoke (Tg)	81	14	115	210
Absorption efficiency (m^2/g)	2	2	2	
Absorption optical depth	0.63	0.11	0.89	1.6

Based on reference 9.

by a collection of individual particles is determined by integrating the effective cross sections, weighted by the density of particles of each size, over the particle radius:

$$b_i(l) = \int \pi r^2\, Q_i(r,m)\,[\mathrm{d}n(r)/\mathrm{d}r]\,\mathrm{d}r$$

where $n(r)$ is the number density of particles of radius r at a position l along a path normal to the horizontal. The subscript i denotes scattering, absorption or extinction. Integrating $b_i(l)$ over the path length then gives the dimensionless parameter, τ, called the optical depth:

$$\tau_i = \int b_i(l)\,\mathrm{d}l$$

The optical depth determines the attenuation of a beam of light (with initial intensity I_0) along a path at a fixed zenith angle ϑ, according to the relationship:

$$I = I_0 e^{-\tau/\cos\vartheta}$$

If one divides the attenuation parameter $b_i(l)$ by the mass of particles per unit volume of air, the resulting parameter, Ψ_i, called the specific scattering (or absorption or extinction) expresses the effective cross section per mass of aerosol present (m^2/g). If b_i (l) is constant along the path length, then once the quantity of dust or soot is known, one can combine the specific scattering (or absorption) with the atmospheric loading of particles per unit area, σ, to calculate the optical depth, τ.

$$\tau_i = \Psi_i \sigma$$

Sample values[19] of specific absorption and extinction parameters are shown in figure 3 for dust and soot particles at both visible and infrared wavelengths. The extinction of visible light by dust and soot particles is very sensitive to particle size for particles with radii from 0.01–0.1 microns. Most nuclear winter studies have assumed that the smoke particles lie within this size range. The studies represent the size distribution by assuming that the number distribution of smoke-particle radii is what is called a "log-normal" distribution (the mode radius, which is the center of that distribution, is the horizontal axis in figure 3). Dynamical processes will, of course, affect the evolution of any real distributions, but particles in the 0.1–1-micron size range tend to remain longest in the atmosphere.

Figure 3 indicates that at the longer wavelength of 11 microns, the extinction is lower by a factor of 10. Because submicron smoke particles absorb short-wavelength light but are nearly transparent to long-wavelength light, a layer of smoke can create an inverse greenhouse effect. For larger, agglomerated particles, however, the absorption at longer wavelengths increases relative to that at shorter wavelengths.

Smoke particles vary a great deal with fuel type and burning conditions. The greater the content of elemental carbon, the stronger will be its absorption. The percent of elemental carbon in smoke aerosols may vary from about 10% for burning vegetation up to 80% or so for oil and gas fires.[20] Smoke from well-ventilated fires tends to be highly oxidized and hence less absorbing. The absorption and extinction efficiencies for smoke particles shown in figure 3 fall in the middle of the range of measured values. The absorption efficiency may be anywhere from 2–5 m^2/g for particle distributions with mode radii ranging from 0.05–0.2 microns. If the smoke comes from fuel with a high carbonaceous content, such as petroleum, the upper limit could be higher. If the smoke is from forest fires, the lower limit could be smaller. Table 3 indicates our assumed range of absorption optical depths.

The height of injection for micron-sized particles of both dust and soot greatly influences their lifetimes in the atmosphere. Small dust particles injected into the stratosphere (above roughly 13 km for northern mid latitudes) may remain there for over a year. Small soot particles might remain[21] in the upper troposphere for one to two weeks or in the lower troposphere for only a few days to one week. These estimates are based on rather sparse data on aerosols in the normal atmosphere. In the conditions of nuclear winter, however, the cooling of the surface relative to the troposphere is expected to slow or stop convection, and hence may inhibit precipitation. Thus the aerosols may prolong their own impact. The scavenging rate for aerosols remains a critical unknown.

The smoke from fires set either by air- or ground-burst bombs rises to heights that depend primarily upon the intensity of the fire. Typical plume heights might be 1–5 km for forest fires (see figure 2) and 1–7 km for urban fires. Firestorms, which occurred in about 5% of the fire-bomb raids in World War II, might lift plumes into the stratosphere. (The plume over Hamburg is estimated to have been 13 km high.)[22]

The dust generated is lifted as high as the mushroom cloud—to a height roughly proportional to a fractional power of the weapon's yield. The bottoms of clouds from warheads of about 500 kt—typical of the warheads on

Table 3. Ranges of key parameters

Parameters	Forests		Inner city		Outer city		Total	
	From	To	From	To	From	To	From	To
Area burned (1000 km²)	100	250	3	12	57	228	160	490
Fuel loading (g/cm²)	0.1	0.5	4	20	1	4		
Quantity of submicron particles emitted (g/g)	0.01	0.04	0.01	0.04	0.01	0.04		
Fraction of smoke remaining after "black rain"	0.5	1	0.5	1	0.5	1		
Total smoke (Tg)	0.5	33	0.6	57	3	228	4	318
Absorption efficiency (m²/g)	1	3	2	6	2	6		
Absorption optical depth	0.0	0.27	0.0	0.93	0.0	3.6	0.0	4.8

Type of region: Forests, Inner city, Outer city, Total.

modern Soviet ICBMs—would rise above 10 km, while only the tops of clouds from 40–50-kt bombs—about the size of warheads on the US Poseidon missiles—would reach this height.

Climate modelers have explored various distributions of the soot with height, but the appropriate representation remains a subject of debate. Most of the early work assumed that the smoke was initially distributed uniformly with height within a certain range. Some critics argued, however, that the smoke might be well mixed with air and thus, more realistically, its density might vary in direct ratio with the air density, which falls exponentially with height. The scale height (the distance at which the air density is 1/e times its value at the Earth's surface) is about 8 km. Perhaps a sum of distributions with different scale heights is the best way to represent the smoke from many fires. The recent National Academy study, in fact, argued[2] that a constant density distribution would result if the number of city fires of a given area (and hence their intensities) were inversely proportional to that area. The importance of height distribution is further illustrated[19] by one sensitivity study: In a one-dimensional model, the surface cooled by 32 °C when smoke was distributed with a constant density in the height range 0–10 km. The drop was only 22 °C when the smoke density varied with a scale height of 3 km.

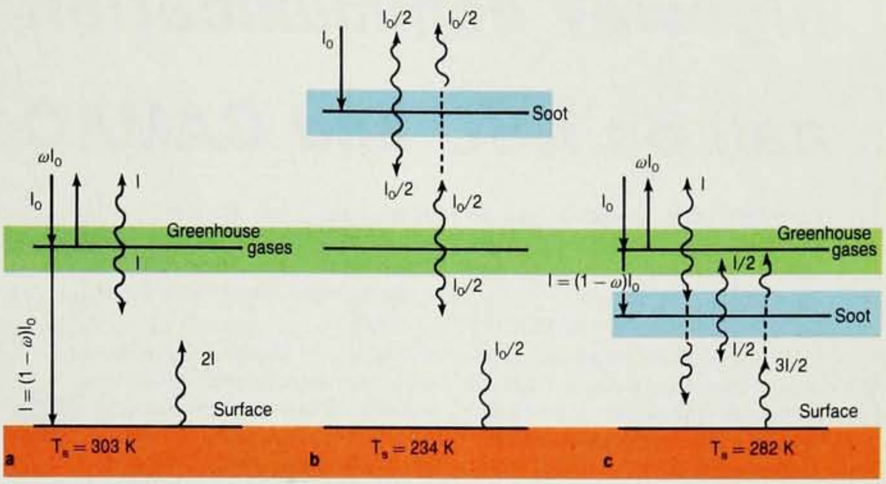
Whatever the initial distribution of smoke in the atmosphere, it may well be altered by subsequent dynamic effects. For example, two recent climate models suggest[12,13] that the upper part of the smoke cloud may be lofted to much greater heights due to heating by the sunlight it absorbs. One of these reports comes from a very detailed climate model that assumes 20 vertical levels in the atmosphere. As shown in figure 4, for a July simulation, with 170 Tg of smoke initially injected between 2–5 km, some fraction of the smoke gets lofted to altitudes of 15–25 km, from which it is removed very slowly. This effect is estimated to increase the amount of smoke remaining after 3 weeks by a factor of 10 in July, and by a factor of 3 in January, over the noninteractive simulation.

The climatic impact of smoke is influenced by its height of injection. Figure 5 illustrates this, using a very simple model of the radiation balance of Earth and its atmosphere. This model ignores convection and surface reflection and treats atmospheric gases, such as water vapor and carbon dioxide, as transparent to sunlight but opaque to infrared radiation. All atmospheric scattering is assumed to occur at the layer of greenhouse gases. Figure 5a shows a two-layer model representing Earth's surface and atmosphere in radiative equilibrium. The surface temperature is 303 K, 15 K higher than the global average of 288 K. In figures 5b and 5c, smoke layers are added and it is assumed that the optical properties of the smoke are the reverse of those of the atmospheric gases—that is, opaque to sunlight but transparent to infrared. In reality, the smoke cannot be transparent to infrared and still radiate it. The case shown is really the limit as the infrared absorption goes to zero and the smoke layer becomes very hot.

When the smoke is above the atmospheric gases (figure 5b), the surface temperature drops dramatically, to 234 K. When it is below those gases (figure 5c), the temperature drop is much less because the atmospheric gases trap and reradiate the infrared from the soot layer and from Earth's surface. Although the numbers represent only very rough estimates of temperatures, the model does illustrate the importance of smoke height.

If the smoke layer is not too thick and not too high, its effect may actually be to warm the surface slightly rather than to cool it: The slowing of surface cooling by convection and the increased infrared radiation may then compensate for the decrease in the incoming sunlight. This possibility is relevant because the amount of smoke produced could conceivably be low. Any such warming would not be as severe or as prolonged as the cooling now predicted.

A uniform distribution of soot would have a greater overall impact on climate than a patchy distribution, especially because the attenuation varies exponentially with the optical depth. One three-dimensional model that addresses the question of patchiness has been developed[11] at Lawrence Livermore Laboratory. In that model, a quantity of smoke equal to that from city fires in the TTAPS baseline scenario is injected at discrete points in North America, Europe, and the Soviet Union. For a July simulation, the smoke cools the areas under the smoke by as much as 30–35 °C, but large areas of the globe are relatively unaffected. The soot concentrations at various times after injection are shown in figure 1. The patchy effect seems rather short-lived, however: After about a month, the distribution



Oversimplified diagram of Earth's radiation balance qualitatively illustrates the impact of smoke height on the climate. The model considers three layers (**a**): Earth's surface, with convective and sensible heat transport ignored; an atmospheric layer of greenhouse gases assumed to transmit all visible light, to absorb all infrared and to reflect with an albedo *w* having an average value of 0.3 for the Earth–atmosphere system; and a smoke layer assumed to absorb all visible light and to transmit all infrared. The incoming radiation I_0 is equal to 0.34 kW/m^2. Temperatures are considerably lower when the smoke is above the greenhouse gases (**b**) than when it is below them (**c**). Figure 5

of smoke originating from discrete sources is similar to that from a uniform distribution. The simulation with one-tenth as much smoke indicated very little impact: Only a few spots on the globe had temperature drops of a few degrees. The spatial resolution of this model is quite coarse (the grid size is $4°\times 5°$) and it includes only two tropospheric layers. Many effects—especially the appropriate smoke removal rate—still warrant further exploration.

The Southern Hemisphere might conceivably be affected by nuclear winter. If so, noncombatants may express greater concern over the size of the superpowers' nuclear arsenals because the countries not directly involved in a nuclear exchange might now appear to have more to risk from a conflict between those two nations. In the first climate model that addressed this question, the dust and soot were constrained[23] within a fixed region of latitude and altitude. The model then tracked the circulation patterns that resulted from this perturbation. Normally the so-called Hadley cells at the equator keep atmospheric circulations in the Northern Hemisphere apart from those in the Southern Hemisphere. In a simulation of nuclear-winter conditions for April, the model indicated that perturbation would cause these separate circulations to merge, so that dust and soot might be carried into the Southern Hemisphere if the aerosols were allowed to move in the model. The same effect was not apparent for a January simulation. The recent Livermore model, which is more interactive than the above model, does indicate some transport of smoke into the Southern Hemisphere in July. The results from two other recent models[12,13] also suggest that as it is lofted, some heated smoke is transported to the Southern Hemisphere. How this smoke might affect the Southern Hemisphere has not been determined.

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