Global Atmospheric Effects of Nuclear War

Our research on the global effects of nuclear war has led to improved calculations of fire development, smoke injection into the atmosphere, and the complex interactive transport of smoke in a global climate model. However, significant uncertainties remain in the chain of calculations that would predict the climatic effects of smoke generated in a nuclear war—the "nuclear winter" effect.

For further information contact Michael C. MacCracken (415) 422-1826.

This article reviews the current research program and recent findings of Laboratory scientists investigating possible global-scale climatic effects from material, principally smoke, that would be injected into the atmosphere as a consequence of a nuclear war. Our research addresses the number and nature of possible fires from a nuclear war, the amount of smoke that could be produced, how it would be injected into the atmosphere and spread over broad areas, the processes that determine the optical properties and lifetime of smoke in the atmosphere, and the influence of varying amounts of smoke on weather and climate.

In the first section below, we give a brief historical account of the recognition of the more important global effects of nuclear war over the past forty years. We emphasize the recent (1982) recognition of possible serious climatic consequences of large amounts of smoke in the atmosphere; we also outline the major uncertainties in our understanding of this effect that make further research necessary. Subsequent sections deal with our research on fire, smoke, and climate.

Global Effects of Nuclear War: Some History

Radioactive Fallout

In the event of a nuclear war, the most violent and destructive effects of blast, heat, and prompt nuclear radiation, although they would produce unparalleled devastation, would nevertheless be localized in the areas immediately surrounding the explosions. For many years, radioactive fallout was the only significant effect that was recognized to extend well beyond the explosion area. There was concern about possible local fallout danger for even the first nuclear explosion, the Trinity test at Alamogordo, New Mexico, in July 1945. In fact, some small but measurable effects of radioactivity from Trinity were observed more than a thousand miles from the test. The development of megaton weapons in the early 1950s increased by more than a hundredfold the potential danger of fallout from individual explosions. The 15-Mt Bravo test in 1954 at the Bikini Atoll produced potentially lethal levels of fallout more than 240 km downwind of the explosion.

The rising fireball of a nuclear explosion at or near the earth's surface sucks up vast quantities of dirt and dust, and the radioactive vapors of the explosion readily condense on this debris, which subsequently falls out generally downwind of the explosion. Such surface bursts produce what is termed local fallout. In a nuclear war involving numerous surface or near-surface bursts, large numbers of radiation casualties would be expected from local fallout. Nuclear explosions detonated high enough so that the fireball does not touch the surface are called air bursts and produce little local fallout. However, the radioactivity of an air-burst explosion (and about one-half that produced by a surface explosion) will be carried into the upper troposphere and, if the yield is large enough, into the stratosphere. This radioactivity is carried by the winds and, in time, spreads throughout the atmosphere. Eventually, various processes lead to the continuing global deposition on land and ocean of the portion of this material that has not radioactively decayed in the atmosphere. Extensive research on fallout mechanisms and on the possible biological consequences of fallout radiation has been carried out since the 1954 Bravo test, in which Marshall Islanders and Japanese fishermen were seriously irradiated. Recent Laboratory research on global fallout is discussed in the box on p. 14.

Ozone Depletion and Dust

In the early 1970s, a new global effect was recognized by LLNL scientists. The large amount of oxides of nitrogen produced in a nuclear fireball could be carried into the stratosphere where these oxides would catalyze reactions that would deplete ozone concentrations. In a nuclear war with many high-yield explosions, the oxides of nitrogen would tend to spread latitudinally in the stratosphere. Over much of the earth, this would lead to a decrease of the layer of ozone that protects the earth from most of the sun's ultraviolet radiation. A 1975 study conducted by the National Academy of Sciences, entitled the "Long-Term Worldwide Effects of Multiple Nuclear-Weapon Detonations,"[1] evaluated the effect of a 10 000-Mt war on the ozone layer. A widespread 50% ozone depletion lasting for a year or more was estimated, with biological consequences estimated to be more severe than global deposition of radiation. Several Laboratory scientists had key roles in this review,[2] and research on the subject has continued to the present at LLNL.

The 1975 Academy study also considered possible global climatic effects from large amounts of dust that could be injected into the stratosphere in a nuclear war. It was concluded, by analogy with the near-absence of global climatic effects following large volcanic eruptions, that dust would not produce significant effects. Ozone and dust effects are discussed further in the box on p. 14.

Smoke

In 1982, the Royal Swedish Academy of Sciences sponsored a new inquiry into the consequences of nuclear war. Paul Crutzen and John Birks, experts on air chemistry, were asked to review the possible atmospheric effects of a war. In the course of reevaluating effects such as nitrous oxide production, ozone depletion in the atmosphere, and possible enhanced ozone production in the troposphere, they recognized that smoke and other chemicals injected into the atmosphere from fires started by the nuclear explosions might have major global atmospheric effects previously not considered quantitatively. They suggested that fires in forests and cities as well as burning oil and gas supplies could produce tremendous amounts of smoke. They specifically estimated the amount of smoke likely to come from forest fires and noted qualitatively the possible serious effects on atmospheric chemistry and the climate. Crutzen and Birks's work was published in the journal *Ambio* in the spring of 1982.[3]

At about the same time, another group of scientists, Richard Turco, Brian Toon, Tom Ackerman, James Pollack, and Carl Sagan, were undertaking a reassessment of the findings of the 1975

Academy study. When they heard of Crutzen and Birks's considerations of the possible effects of smoke, they expanded their study to include the first quantitative assessments of the global climatic effects of large amounts of smoke. They circulated an early version of a report on their work in the spring of 1983, and in December 1983 published a final version in the magazine *Science*, entitled "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions."[4] (This paper is referred to as the TTAPS report, an acronym formed from the authors' initials.)

The TTAPS report conjectures that a nuclear war involving over 10 000 explosions with a total yield of 5000 Mt could produce and inject into the atmosphere over 200 Tg (200 million tonnes) of smoke. Spread over the northern hemisphere, the smoke would absorb most of the sun's energy high in the atmosphere. Temperatures over major land areas could drop by about 35°C and remain below freezing for more than a month. If these predictions are correct, the phrase "nuclear winter" is an apt one for the effect.

A companion report to the TTAPS study in the same issue of *Science*[5] by twenty scientists, mostly biologists and ecologists, attempted a first assessment of the biological consequences of nuclear winter. It concluded that, in addition to the direct effects of a nuclear war, extended subfreezing temperatures and low light levels would have further catastrophic effects and that "the population size of *Homo sapiens* conceivably could be reduced to prehistoric levels or below, and extinction of the human species itself cannot be excluded."

The TTAPS study required a chain of uncertain assumptions concerning the nature of a nuclear war, how much smoke would be generated, how high it would rise, how long it would remain in the atmosphere, and how effectively it would absorb sunlight. Furthermore, the estimates of temperature change were based on results from a highly simplified model of the global climate. Their one-dimensional radiative-convective model treats only the vertical structure of the atmosphere; it neglects the land and ocean difference, horizontal spread of smoke, diurnal and seasonal variations of solar radiation, and many other factors.

By the spring of 1983, many atmospheric scientists were aware of Crutzen and Birks's work and had seen early versions of the TTAPS report. Several research groups undertook to improve on the TTAPS analysis by doing calculations using more realistic global climate models. These groups included the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, the Computing Center of the Academy of Sciences of the Soviet Union in Moscow, the Atmospheric and Geophysical Sciences Division at LLNL, and the Los Alamos National Laboratory.

To date, new results have mainly been obtained in the areas of global spread of smoke and the consequent climatic effects. For the new investigations, the researchers retained most of the original assumptions of Crutzen and Birks and of TTAPS concerning how much smoke could be generated, what kind, and what would be the early-time phenomena. Under these assumptions, the new results, although differing slightly in detail from one another, agree qualitatively with the basic findings of the TTAPS study. Specifically, if a sufficient amount of black smoke is injected high into the atmosphere during a warm part of the year, then significant climatic cooling of land surfaces can occur. The average cooling over land calculated in the more realistic global models is significantly less than the maximum cooling obtained in the TTAPS work, although the temperature changes over the centers of continents were similar to those of TTAPS. For a given temperature change, the newer calculations tend to give higher final temperatures than did TTAPS because the assumed initial temperatures in TTAPS were substantially lower than typical midcontinental summer values.

The qualitative agreement among these results is somewhat deceptive, however, not only because the new work starts with the same assumptions about smoke generation and injection as did TTAPS, but because much of the global circulation phenomenology, itself, needs to be reexamined in the light of the new conditions obtained with injection of large amounts of smoke into the upper atmosphere. What is clear is that the early work of Crutzen and Birks and of TTAPS has raised a serious question. Obtaining even approximate answers to it will take much more extensive research.

A broad review of the predictions of Crutzen and Birks, of the TTAPS group, and of subsequent research findings by others has been carried out by the National Academy of Sciences and was announced in December 1984.[6] The new Academy report confirms the possibility of a nuclear winter. It also highlights the substantial range of uncertainty in the predictions and the need for further research.

The Laboratory's Global Effects Program

The Laboratory has been involved in research related to the global effects of nuclear war for more than 25 years. In early 1983, we initiated exploratory studies of the nuclear winter effect following publication of the Crutzen and Birks article and the draft TTAPS study. A formal research program on this topic was begun at LLNL in late 1983, funded primarily by the Laboratory's defense programs. The elements of our program are:

- To estimate plausible ranges for the amount of material that might be ignited.
- To estimate the development, intensity, and spreading rate of fires.
- To calculate, under various conditions, the height to which fire plumes might rise and the vertical distribution of injected smoke.
- To determine the evolution of the physical, chemical, and radiative characteristics of smoke in the rising plume and as the particles interact with water vapor, clouds, and rain.
- To calculate the effect of smoke particles on solar and infrared radiation.
- To use atmospheric models to calculate the spreading and scavenging of smoke, from plume to global scales, and the induced effects on weather and climate.
- To develop an overview of the potential biological and ecological consequences of a major exchange.

Even the broad range of topics included in the LLNL research program does not adequately address many areas of the problem. Thus, we are also involved in cooperative efforts with the Defense Nuclear Agency (DNA). In addition, we have assisted the National Climate Program Office in developing a national plan to augment the efforts now under way by the DOE and the DNA.[7] With several years of research, we believe that the major uncertainties in the predictions can be significantly reduced.

Scenarios

The predicted cooling of land surfaces is highly dependent on the amount of smoke that would be generated in a nuclear war. For total quantities of smoke less than about 50 Tg, the cooling effects would probably be primarily regional rather than hemispheric or global. (Fifty teragrams is about ten times the current annual emission of smoke from forest fires in the U.S.) For more than about 300 Tg of smoke, it is likely that there could be climatic effects, darkness, and low temperatures over much of the northern and southern hemispheres. Adding much more smoke would not make the effects much more severe but would probably prolong them. For quantities of smoke in the range from about 50 to 300 Tg, spanning the values considered by TTAPS, the predicted temperature changes are strongly dependent on the amount and characteristics of the smoke, the height at which it is injected, the rate of spread, the time of year, and many other factors. Each of these factors depends critically on what kind of nuclear exchange is assumed, the combustible nature of the targets, and how much fuel would burn. To deal with these problems, a series of hypothetical nuclear wars or scenarios are being constructed to span possible ranges.

Previous studies have made rather arbitrary assumptions in developing baseline nuclear war scenarios. For example, Crutzen and Birks used a scenario prepared by advisors to the journal *Ambio.*[3] This group constructed what they refer to as a "limited" scenario, including nearly 15 000 warheads totaling about 5750 Mt. In this scenario, all cities of NATO and Warsaw Pact countries with populations of over 100 000 people and all other cities with populations greater than 500 000 were targeted with a total of about 5000 warheads on about 1100 cities. In addition, they assumed that about 6600 warheads would be directed to other

Radionuclides, Nitrogen Oxides, and Dust

One of the most widely known effects expected from a nuclear war is fallout—the deposition of radioactive material produced by nuclear explosions. In addition to fallout, the interaction of clouds of radioactive debris with precipitation systems can result in the localized deposition of radioactive material, a process termed rainout.[8] Relatively intense fallout or rainout could occur adjacent to and downwind of targets subject to near-surface nuclear explosions. The most likely targets for surface bursts are hardened missile sites and command centers. Protection from intense local fallout and rainout requires personnel to be evacuated from the affected areas or to remain in adequate shelters for several weeks.

Nuclear explosions occurring well above targets are called air bursts. Such explosions would create the most widespread fires and blast damage. The radionuclides produced would tend to be injected high in the atmosphere and dispersed over large areas. Except in regions where relatively fresh debris is carried to the ground by rain in precipitation systems, the fallout radiation doses would likely remain well below critical levels, especially if protective actions were taken.[9]

In the early 1970s, scientists at LLNL and elsewhere recognized the potential global effects on stratospheric ozone of the nitrogen oxides that are created in nuclear fireballs. Explosions of about 0.5 Mt or larger can loft nitrogen oxides into the stratosphere, where they could interact chemically to reduce the concentration of ozone. Stratospheric ozone absorbs a large fraction of the ultraviolet radiation emitted by the sun, thereby protecting the surface of the earth from excessive exposure. A substantial reduction in ozone would allow increased ultraviolet radiation to reach the surface, which could, in turn, lead to severe sunburn in a short time[10] and damage to unprotected plants and animals. Adequate clothing or shelter would protect humans.

The amount of injected nitrogen oxides and the resulting extent of ozone depletion depends on the yield and number of explosions and, thus, on the character of the war that is assumed. For a war scenario involving about 10 000 Mt of high-yield weapons, estimates made in the 1970s indicated that stratospheric ozone would be reduced by up to 50% and that the effect would last for several years. However, the trend to warheads with smaller yields has led to lower estimates of oxides injected into the stratosphere and, consequently, lower ozone depletion. In addition, because smoke and dust from the explosions may block much of any increased ultraviolet radiation, estimates of the potential exposure at the surface have been further reduced.

The 1982 study of Crutzen and Birks[3] suggested that the presence of large amounts of nitrous oxide in the troposphere could actually favor chemical processes leading to the production of ozone. Their studies indicated that, in the absence of smoke, smog levels typical of Los Angeles might develop. Subsequent investigations at LLNL suggest that smoke would, indeed, prevent the photochemical reactions that produce smog and that the essential ingredients (nitrous oxides and hydrocarbons) that might create smog may be scavenged more rapidly than the smoke particles.[11] By the time that solar radiation would again be intense enough to induce smog, it is likely that the smog-producing chemical ingredients would have largely disappeared.

The climatic effects of dust that would be injected into the atmosphere as a result of many surface bursts have been a concern for many years. The National Academy of Sciences study of 1975[1] briefly examined the potential climatic effects of dust injection and concluded that the effects would not be significantly different from those following major volcanic eruptions such as Tambora in 1815 or Krakatoa in 1883. Although eruptions during the past may well have caused unusual and cooler weather, they have not (except near the eruption) seriously affected human, plant, or other animal life. It has been suggested that Tambora may have induced what has been called "the year without a summer" in the northeastern U.S. and Europe.[12] The year was characterized by locally serious crop failures due to unseasonal frosts and snowfalls; however, the effects were small in most areas, and near-normal weather patterns returned the following year. Krakatoa produced temperature decreases of at most a fraction of a degree in hemispheric average temperature.

military targets, and 3100 warheads would be used on industrial and energy-related targets.

The TTAPS baseline assumed that about 10 400 explosions and 5000 Mt would be used, with the yield distributed among several types of target. They also considered numerous other scenarios that ranged from 100 to 25 000 Mt. The latter number is actually about twice the total yield of the approximately 50 000 weapons now in existence, according to the recent National Academy of Sciences (NAS) report.[6] For the Academy study itself, it was assumed that half of all existing weapons would be exploded, for a total of about 25 000 explosions and 6500 Mt.

In such simplified scenarios, many matters of importance tend to be overlooked. For instance, no rationale (or evidence) exists for targeting all large cities around the world, or for other aspects of the *Ambio*, TTAPS, or NAS scenarios. Multiple weapons on important military targets would reduce the number of fires that might be started. The proximity of military targets to developed areas and forests would also alter the number and kinds of fires started.

To gain a better perspective, we are working with the DNA to develop a range of more detailed scenarios. They will incorporate data on the makeup of the U.S. and Soviet arsenals, categories of possible targets and target areas, and various practical considerations. Our intent is to establish a set of building-block scenarios that can be combined to provide a range of inputs to the calculations.

In addition to developing a range of possible scenarios and target categories, we must estimate the amount and type of combustible fuel in each of the target categories. The TTAPS study, for example, assumed continental-average forest coverage around all military targets. In fact, most U.S. missile fields are located in fields or prairie, which would generate much less smoke than forests. Since urban fires are potentially the most important source of smoke, we are conducting studies to estimate the fuel loading of typical cities.

What Is Injected into the Atmosphere?

To predict the climatic effects of a nuclear war, we must know the amount of smoke that is produced by fires, the chemical and optical characteristics of the smoke, and the altitudes at which the smoke is initially injected into the atmosphere. The amount and properties of smoke depend on the fuels and the conditions under which they burn. We must estimate not only the total amount of fuel actually consumed by the fires but also how the fires burn.

Smoldering fires of low intensity produce relatively large amounts of smoke per unit weight of fuel consumed. The smoke remains relatively low in the atmosphere (a few kilometres), is whitish or gray, and acts primarily to scatter light rather than absorb it. Flaming fires produce less total smoke, but the smoke is blacker and tends to absorb much of the light striking it. Intense flaming fires can release large amounts of energy and can loft black smoke into the upper troposphere (about 5 to 10 km above the surface of the earth). Smoke lofted to these higher altitudes could induce more cooling at the surface of the earth than smoke at altitudes of a few kilometres because the particles would absorb incident solar radiation in the troposphere above the natural "greenhouse" gases.[13] In the unperturbed atmosphere, smoke higher in the troposphere would be expected to remain longer than smoke injected nearer the surface because there is less precipitation at higher altitudes. Very intense fires may even inject some smoke into the stratosphere where it would remain for even longer times. (The dividing line between the troposphere and stratosphere is called the tropopause and varies with latitude. In our models for smoke injection, we have selected a globally averaged altitude of 11.5 km for the tropopause.)

Research on the Initiation and Spread of Fires

Of the two types of fire that have been considered in global-effects research, more is known about the initiation and spread of fires in wild lands than in urban areas. Crutzen and Birks proposed wild-land fires as a large source of smoke following a nuclear exchange. They did not treat urban fires at all, although they included an estimate for the burning of fuels stored above ground. They suggested that in a nuclear war, on the order of a million square kilometres of forest would burn in the northern hemisphere, emitting about 7% of the weight of fuel as smoke for a total of about 200 Tg of smoke. The TTAPS group estimated that about 80 Tg of smoke might be produced from burning forests. They assumed the area of forest fires to be half a million square kilometres and a more reasonable smoke emission rate of about 3%. In a recent, more detailed analysis of possible targets in forested and other wild-land areas, Small and Bush argue that only 200 000 km^2 of wild land might be expected to burn.[14] Because much of the region surrounding targets is grassland rather than forest, and because the resulting fuel load and emission rates are lower, they estimated that, at most, 2.2 Tg of smoke would result from these sources. Others have suggested that this estimate may be somewhat low.[15]

From measurements of the optical properties of smoke produced from forest fuels, we now know that such smoke is less absorbing of solar radiation than was assumed by TTAPS. Furthermore, the smoke from forest fires may not rise as high into the atmosphere as the TTAPS report assumed. Because of these factors, we now consider the smoke from wild-land fires to be a much less important contributor to the nuclear-winter effect than smoke from urban fires.

The amount of smoke that would be produced from urban fires is difficult to estimate. Large forest fires do not serve as a useful analogy because they burn quite differently. In addition, forest-fire fuel loadings are only about one-tenth those of an average suburban area and perhaps one-thirtieth those of a typical city center. Detailed current surveys of the amounts of burnable material present in cities are not available. The amounts and types of combustible material are expected to be different in various countries of interest and even from region to region in each country. In addition, we do not understand how an entire city might burn after a nuclear attack. Good estimates of the amount of smoke produced by a large fire, one in which 50 to 250 km^2 of a city are ignited at once, are unavailable. The TTAPS baseline scenario assumes a total urban area of 230 000 km^2, equivalent to about 2000 cities the size of San Francisco, would be completely burned. Many significant questions about smoke from city fires remain unanswered, including for example:

- Whether or not the fuel in the severely blast-damaged area of a city might be so covered with debris that it does not burn much, if at all.
- How well the fires are supplied with oxygen.
- The peak temperatures that are reached.
- Whether fires are hot enough to ignite neighboring structures by thermal radiation.
- How much smoke is produced by various fuels, particularly the newer synthetics burned under extreme conditions.

Laboratory measurements of smoke emissions under differing temperature conditions are available for some fuels. However, because we cannot yet predict the conditions of a nuclear-explosion-generated fire, they are of limited value.

To approach the problem of urban fires, we have obtained detailed codes that were developed as part of civil-defense research programs in the 1960s. The codes were used to characterize the burning of cities after a nuclear blast, and can be helpful in estimating ignition, fire-spread in various parts of a city, and how much fuel would be expected to burn.

These models still have many limitations. For example, the codes assume that each building of a given type will burn in a prescribed manner. (In general, a fire is assumed to build slowly over about half an hour, become a "stage-three" fire in which the entire building is engulfed in flames in an hour, and then die down after roughly another hour, as though one were dealing with an isolated building.) Possible effects that may be important, such as immediate flashover to flaming conditions, due to high deposition of energy within an enclosed room from the fireball, are not treated.

The civil-defense codes also do not adequately treat the problem of whether or not fires start and spread in those areas of a city that are essentially reduced to rubble by blast. It is necessary to develop prescriptions for fire initiation and spread in such areas. Although the older codes were helpful for civil-defense assessments, they may require substantial modifications to provide an adequate picture of the kind of urban fire with which we are concerned.

Despite these limitations, we have used the codes for some exploratory calculations. If urban fires develop as now modeled, and fuel loadings are less than 10 g/cm^2, then the rates of energy release will not be high enough to provide what are believed to be necessary conditions for a firestorm, such as occurred at Hamburg in 1943. (The estimated energy-release rate at Hamburg was 1.4×10^5 W/m^2 over an area of about 12 km^2.) We also have found that the total amount of fuel that would be burned, the intensity of the fire, and the area over which the fire would spread depend on the particular fuel distribution that is assumed.

We have explored the dependency on fuel distribution and other factors with calculations for a "uniform" city and for a representation of San Jose, California. The uniform city consisted of identical two-story frame houses equally spaced in identical housing tracts. For the basic calculations, the average fuel loading was 3 g/cm^2. The curve labeled "uniform city" in Fig. 1 shows the cumulative fuel consumption versus time as predicted by the fire-spread code. For these calculations, a 1-Mt airburst was assumed. The calculation neglects any burning in the heavily blast-damaged region out to about 9 km (the 25-kPa level) and assumes that fires are ignited by the thermal pulse out to about 13 km (where the thermal energy is 325 kJ/m^2). The code predicts that about 4 Tg of fuel is burned in the first seven hours and another 2 Tg in the rest of a 24-hour period. In addition to this basic calculation, numerous additional calculations were performed varying parameters such as wind speed, building density, fuel loading, range of fire brands, and frequency of secondary fires.

A second set of simulations used a representation of the greater San Jose region as it was in 1968 (data available from old civil-defense studies) to analyze how a more realistic city would burn. Again a 1-Mt airburst was assumed. However, the area surrounding the burst point was of relatively low building and fuel density and there were many vacant tract areas involved. As a consequence, the potential fuel for burning was much less than for the uniform city calculation. Figure 1 includes a curve for the cumulative fuel burned with time for the San Jose (1968) calculations.

The examples of the uniform city and San Jose dramatize how different, by more than a factor of ten, fuel consumption (and implicitly smoke production) can be for different city representations and aim-point choices. Much more effort is needed in characterizing fuel distribution of urban areas.

In the coming year, we will develop new fuel-loading descriptions for several typical cities. These descriptions will enable us to estimate how the total amount of fuel consumed varies with city type so that we can make comparisons with other estimates. We

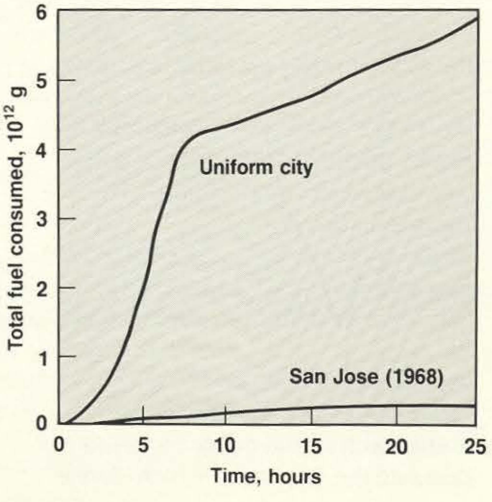


Fig. 1

The cumulative fuel consumed outside the blast-damaged area of a uniform city is roughly ten times greater than that calculated for the area of northwestern San Jose, California, as characterized in 1968. Such differences illustrate the need to develop additional and more accurate fuel-loading descriptions, which will enable us to determine how the total amount of consumed fuel varies with city type and configuration.

will also be developing a new model that can describe how blast-damaged areas burn. Our intention is to test our models against available observations of past fire spread and possible future experiments. Although understanding how fires generated by nuclear explosions really burn and how much smoke they actually produce are difficult problems, an approach that combines both experiments and models should help to address these two important issues. The national research plan recommends such an approach.

Plume-Rise and Smoke-Injection Altitude

The height to which smoke is lofted by the heat of a fire is important because smoke lofted to high altitudes is expected to have a much longer lifetime than smoke injected at altitudes closer to the earth's surface. If all the smoke from fires were injected at low altitudes (below about 2 km), not only could it be removed relatively quickly by rainfall but also only very limited cooling (or even an increase) in surface temperature would be expected while the smoke remained. The amount of light reaching the surface could, nonetheless, still be substantially reduced.

Several groups have investigated the atmospheric dynamics associated with the smoke plumes from intense fires (those with energy-release rates of about 10^5 W/m^2 and greater). Two recent papers relied on an analytical model that accurately describes the rise of small-scale plumes to estimate the height of smoke injection for the much larger fires in which we are interested.[16,17] Although the estimates appear to be reasonable, it is not known how accurate they are. For the TTAPS study, the heights to which smoke might be carried above a fire were not explicitly calculated. The authors assumed a range of injection altitudes between 1 and 5 km for forest fires and between 1 and 7 km for urban fires. Five percent of the urban fires were assumed to be firestorms that lofted smoke from 5 to 19 km.

Penner *et al.*[18] have applied a numerical hydrodynamic model to calculate the heights to which smoke could be lofted. Since our effort began, other groups using similar models have obtained results that are consistent with our simulations for very large fires.[19] No models to date adequately address the significant issue of the extent to which rain, forming in the convection column, scavenges the smoke as it rises and spreads.

Using our model to simulate a hypothetical line-source (that is, two-dimensional) fire, we can investigate the influence of a variety of factors, such as fire intensity, condensation of water vapor, and background wind speeds (see Fig. 2a–c). We are currently investigating some of these factors with a version of the code that allows the more realistic simulation of a full three-dimensional fire. The three-dimensional code is relatively expensive to run, and the results shown in Fig. 2d tend to confirm those obtained with the two-dimensional code. In particular:

- For intense fires (with energy-release rates of 8.9×10^4 W/m^2 over a 5-km-radius circle that may be typical of urban centers), most of the smoke is lofted to altitudes between 5 and 10 km. (See Fig. 3 for comparison of our results with the TTAPS distributions for comparable amounts of smoke.) For these fires, significant amounts of water vapor may condense, raising the possibility of early scavenging of smoke, depending on its chemical and physical characteristics (see below).
- For fires of medium intensity (with energy-release rates of 1.4×10^4 W/m^2 assumed typical of suburban areas), most of the smoke is lofted to altitudes between 2 and 8 km.
- For fires of low intensity (with energy-release rates of 2.3×10^3 W/m^2, typical of forest fires), most of the smoke remains below 3 km.
- The smoke directly above a fire reaches somewhat higher altitudes than the altitude to which most of the smoke eventually settles and disperses.
- Background winds tend to limit the upward movement of smoke, thereby decreasing the peak altitude of injection.
- Water condensation within a plume releases latent heat and can add buoyancy that will cause the smoke to

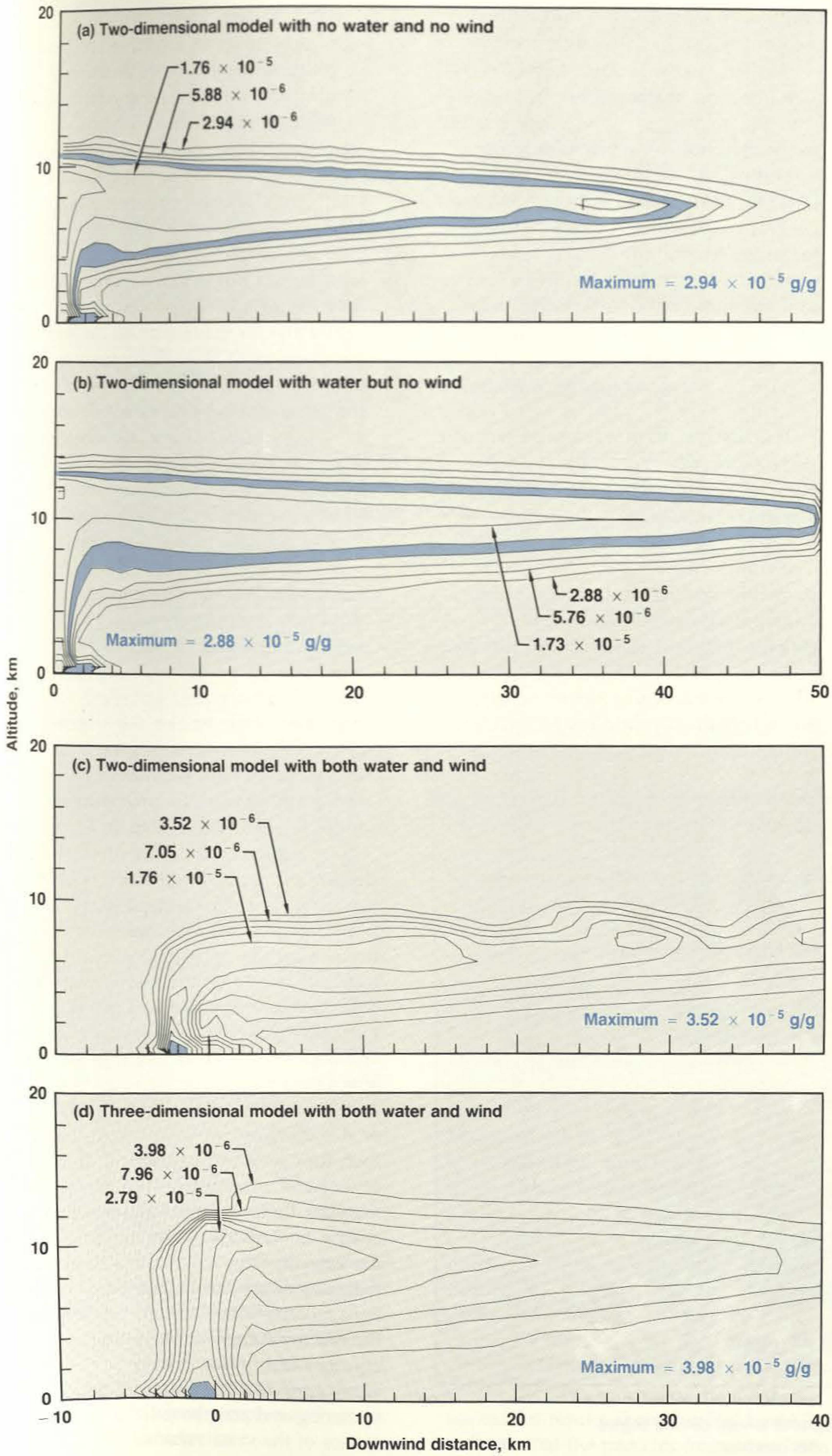


Fig. 2

Simulations of a high-intensity fire (8.9×10^4 W/m^2) allow us to determine how smoke is injected into and spreads through the atmosphere. The contours, shown here as solid lines, indicate the maximum mass-mixing ratios of smoke, expressed in units of grams of smoke per gram of background air. The interval between each contour is one-tenth of the maximum calculated for a given simulation. (a) Smoke contours are shown for the case without condensing water vapor or background wind. (b) When a global-average relative-humidity profile is assumed, water vapor carried aloft in the convection column condenses at high altitude, and latent heat is released to drive the smoke higher. In both (a) and (b), only one-half of the smoke profile is shown because these two-dimensional simulations are symmetric about the origin of the smoke. (c) Background wind added to the two-dimensional simulation with water carries the smoke to the downwind side of the source region. (d) For a three-dimensional simulation, both condensing water vapor and background wind are assumed to be present. With background wind, the smoke lofted in our two-dimensional model does not reach an altitude that is as high as that for the more realistic three-dimensional case. Note that the horizontal scales in both (c) and (d) are shifted to the right to show asymmetric smoke profiles about the origin.

be lofted from 2 to 3 km higher than the peak altitudes calculated without considering water condensation.

- Injection heights, thus, can vary with the amount of water vapor present in the atmosphere in the area of fires.

Our calculated altitudes for smoke injection from fires of various sizes are generally consistent with those assumed for urban fires in the TTAPS study. Our results do indicate that lofting of smoke into the stratosphere is unlikely unless the background atmosphere is highly unstable and the fires are extraordinarily intense (as was the case in Hamburg).

Radiative Properties of Smoke

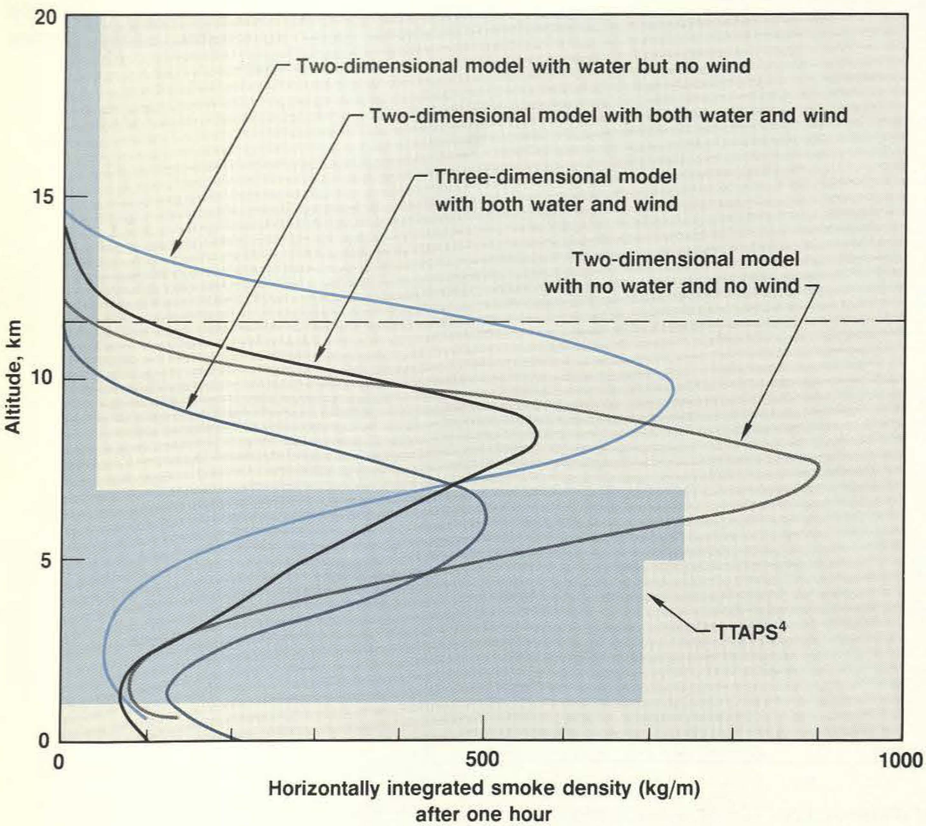
The radiative properties of smoke particles depend on three important physical characteristics: the composition, the size, and the shape of the particles. The composition of particles affects their scattering and absorption properties. Particles with a high fraction of elemental carbon appear black and are effective absorbers of sunlight. Particles with a low fraction of elemental carbon are lighter in color and tend to scatter sunlight more than they absorb it.

Particle size has a particularly significant effect on radiative properties. To compare the effects of different particle size, we have done calculations in which the total smoke mass is constant and the total number of particles varies with size (i.e., many small particles or fewer larger particles). Spherical particles that are much smaller than the wavelength of sunlight (much less than 0.1 μm in diameter) are effective absorbers but poor scatterers of light. Particles that are much larger than the wavelength of sunlight (greater than 1.0 μm in diameter) are both poor absorbers and poor scatterers. Particles that are similar in size to the wavelength of sunlight (the center of the visible solar spectrum is near 0.5 μm) are very effective scatterers of light and may or may not be effective absorbers, depending on their composition. Because real smoke is made up of a distribution of particle sizes, it is necessary to perform numerical calculations to determine the wavelength dependence of the absorption and scattering properties of the smoke. For smoke from urban fires, the fraction of the total attenuation of light (scattering plus absorption) that is due to scattering ranges typically from 50 to 70%.

The radiative properties of smoke also depend on particle shape and whether the particles are homogenous or nonhomogenous in composition. All of the climate assessments done to date have assumed that the smoke particles are homogenous spheres. The microphysical processes of coagulation and condensation (discussed below) affect the composition, size, and shape of particles. If the particles are mostly liquid or if liquid condenses on smoke particles, then they tend to be spherical. If, on the other hand, the particles are dry, solid material, then they tend to form long chains. Soot, in particular, is noted for its tendency to form long chains. Particles that are nonspherical absorb and scatter light more effectively than a sphere of the same volume. For example, an ellipsoid with a length three times its width is up to 20% more effective in scattering and absorbing light than a sphere of the same volume.

Fig. 3

The integrated smoke density is shown as a function of altitude for each of our four simulations for high-intensity fires depicted in Fig. 2 (solid lines). Depending upon background conditions, most of the smoke from an intense fire is lofted to altitudes between 5 and 10 km. In general, the lower-altitude injections of smoke that were assumed by TTAPS[4] (see shaded region below about 7 km) correspond quite well to our patterns for low- and medium-intensity fires, which are not shown in this figure. Our simulations of a high-intensity fire indicate that little smoke is lofted above the tropopause (dashed horizontal line) and into the stratosphere. Note: the three-dimensional model curve is plotted ten times less than its actual values to permit comparison with the other curves.



The surface, clouds, and atmosphere at temperatures near 27°C radiate long-wavelength (4- to 20-μm) infrared radiation. The so-called "greenhouse" gases in the normal atmosphere, principally water vapor and carbon dioxide, absorb and trap some of the infrared radiation emitted from the surface and lower atmosphere and maintain the average earth temperature above freezing (see Ref. 13). A cloud of black smoke with particles in the micrometre range would, if sufficiently dense, absorb most of the incident sunlight before it reaches the earth's surface. The land surface would cool by radiating infrared radiation as it does on a clear night. The same micrometre-size smoke particle that is a good absorber in the visible is a relatively poor absorber, down by about a factor of ten, in the infrared and therefore is not very effective in slowing the loss of infrared radiation from the earth. If, however, there is substantial coagulation of the smoke particles, and particularly if they form chains comparable in length to infrared wavelengths, then absorption at these wavelengths can become more effective and the radiative cooling of the darkened earth would be slowed.

The radiative properties of smoke can vary greatly depending on its physical properties, which are controlled, in turn, by microphysical and chemical processes. The effects of variations in the optical properties of smoke on the estimated climatic impact for large smoke loadings have been investigated by Ramaswamy and Kiehl[20] and by Luther.[21] For a given mass of smoke in the atmosphere, the estimated surface-temperature reduction can vary by about a factor of two for variations of the optical properties between plausible limits.

Microphysics

In our research, the term "microphysics" refers to the physical and chemical interactions of smoke particles with one another and with the environment. Two major microphysical processes, coagulation and scavenging, have the potential to affect substantially the projected climatic response to a massive smoke injection.

Coagulation involves smoke particles colliding and adhering to form larger particles. It determines the size distribution of the assortment of smoke particles and is the primary factor in determining how much the particles affect solar and terrestrial radiation fluxes. These fluxes, in turn, determine surface temperatures and the climatic response.

Scavenging involves the interactions of smoke with water vapor, condensed water, ice, and snow. It can lead to the removal of smoke particles from the atmosphere by rain or snow and is the primary determinant of how long particles remain in the atmosphere. Neither the study of Crutzen and Birks nor the TTAPS study included a detailed consideration of coagulation or scavenging during the spread of smoke at early times after injection.

Because so many microphysical interactions are possible, coagulation can be important on both the short time scales that are associated with the lofting of smoke plumes above a fire and on the longer time scales that are associated with the spreading of smoke on a global scale. Coagulation was considered in the TTAPS study, but because it assumed that smoke was instantaneously spread throughout the northern hemisphere, the particles were, on average, so far apart that they seldom collided and did not coagulate to a significant extent.

We have developed a new computer code that is capable of describing the coagulation of particles as they become dispersed. At early times within dense smoke plumes, the particles tend to be close together and to coagulate quite rapidly. At later times but still in the plume phase, the particles are so widely dispersed that coagulation can be ignored. During the time of plume injection (the first hour), we find that unless the emission rate for smoke is much greater than 3% of the fuel being burned, the coagulation of particles is not sufficient to alter significantly the optical properties of the smoke. In contrast, even with conservative estimates of the initial smoke density expected on regional scales, our results shown in Fig. 4 and 5 indicate that the particles may coagulate enough in the first week to decrease their ability to absorb and scatter solar radiation by up to 40%. Optical depth is the term used to measure the vertically integrated extent of absorption and scattering. A 40% decrease in optical depth is equivalent to having 40% less smoke. These effects have been investigated by Penner.[22]

The microphysics of scavenging is even more complex than that of coagulation. Interactions between smoke and the water in clouds, rain, or ice must all be taken into account. Precipitation and the removal of smoke by scavenging may occur as a result of such interactions.

In the normal atmosphere, a balance is reached between the number of cloud condensation nuclei, or seed particles, entering a cloud and the amount of available water vapor. Under such conditions, water vapor condenses on the nuclei, forming droplets that further coalesce and grow into raindrops or snowflakes that can become large enough to fall to the ground.

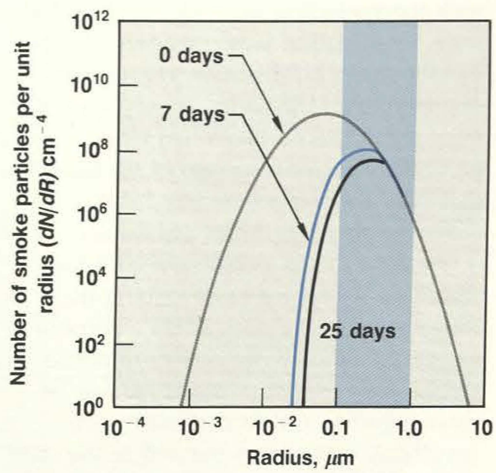


Fig. 4

The number of smoke particles per unit of radius is shown as a function of particle radius for an initial loading of 800 pg/cm^3. Loading is a measure of the density of smoke. The size distribution of smoke particles helps to determine their optical properties. Particles that are in close proximity in the smoke (higher on the curves) coagulate to form fewer, larger particles. Within seven days after an injection of smoke, the number of particles in the optically important size range (between 0.1 and 1.0 μm) may be significantly reduced due to coagulation.

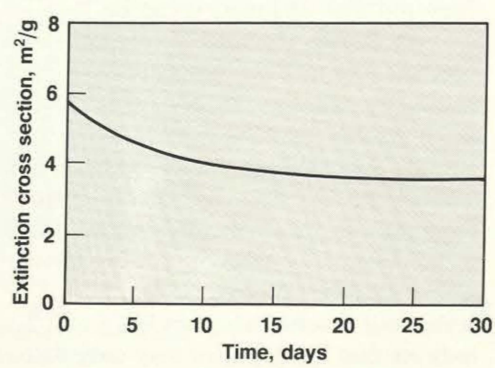


Fig. 5

The extinction cross section of smoke is a measure of how effectively a gram of smoke interacts with light. As the number of small smoke particles decreases over time (see Fig. 4), the extinction cross section also decreases. The 40% decrease shown here reduces the optical depth of smoke by the same percentage and would be equivalent to a 40% reduction in the amount of smoke if optical properties were not changing.

Depending on their chemical composition, smoke particles in the plume above a fire may act as cloud condensation nuclei. However, their number may be so great relative to the available water vapor that only very small water droplets can be formed. Such droplets are too small to fall as rain; at the same time, they are too large to be moved enough by Brownian motion and other processes to coagulate into larger drops that would fall. This condition of too many condensation nuclei is called overseeding and may substantially limit the scavenging of smoke particles by precipitation in a fire plume. Crutzen and Birks mentioned the possibility that overseeding might occur, but no attempt was made to assess its importance. The TTAPS study noted but took no account of overseeding, and instead simply assumed that 25% of the smoke would be scavenged through various mechanisms in the fire plumes.

If overseeding takes place, rain is unlikely to occur directly above a fire. Capping clouds, which are observed above many fires, form as the result of condensing moisture, but we do not know whether the drops of moisture condense on the smoke particles generated by the fire or on the background aerosols that are naturally present in the atmosphere. Indeed, water vapor will not condense on all types of particles. Small particles must contain a small fraction of soluble material if they are to serve as condensation nuclei. Hydrophobic or water-repellent material, such as pure soot or oily particles, will not function as condensation nuclei unless the particles are fairly large.

If, on the other hand, overseeding does not take place, then it is quite possible that rain will occur above a fire. From our calculations involving smoke plumes from intense fires, we find that more than 1.5 times the amount of water that is usually necessary to initiate rain is available to condense. In our model for an intense fire, the total amount of condensing water is 100 times (by weight) the total amount of smoke. If rain forms, falls, and sweeps up smoke particles, less smoke would be carried to high altitudes. We do not have good estimates of the extent of such scavenging. It has been suggested that the black rain observed from the fires after the bombing of Hiroshima was caused by such scavenging.

Calculations with models that treat clouds by accounting for the dynamics of a fire and the rise of smoke plumes are complex, use large amounts of computer time, and do not yet treat the formation of rain in detail. Although the models include equation to describe the formation of droplets, ice, and rain, the adjustable equation parameters are selected to yield results consistent with what happens in the normal atmosphere. The models do not treat interactions with smoke or other pollutants.

The rain that might occur above a large-scale fire generated by a nuclear explosion requires a more detailed approach. We are currently developing a computer model that is an extension of our coagulation model, that will incorporate other relevant mechanisms, and that will enable us to answer questions regarding the fate of smoke. This model will be run in conjunction with the plume model to assess early-time scavenging and with the global-scale model to assess longer-term removal of smoke.

To assess the optical properties of smoke after it has come into contact with water, we must model the interaction of smoke particles with water vapor and drops. Some measurements have shown a significant change in the size distribution of smoke particles after interactions with a capping cloud above a forest fire. Apparently, interaction with the cloud either enhances the coagulation rate of dry smoke particles or causes them to swell as they accumulate water, in either case creating more large particles. Recall that spherical particles tend to become less efficient absorbers of sunlight as they grow larger than the wavelength of the light. We do not know, however, how effectively light might interact with irregularly shaped, swollen smoke particles. It is believed, however, that a carbon smoke particle surrounded by water absorbs more visible light than the particle and water drop acting separately.

Climate Changes Due to Smoke Injection

As we have discussed, the presence of smoke particles in the atmosphere perturbs the normal passage of solar radiation. Initial studies by several groups using numerical models have shown that substantial surface cooling can occur if large amounts of highly absorbing smoke particles are injected high into the troposphere.

A major focus in presenting these results has been on developing estimates of the temperature change on land surfaces in the midlatitudes of the northern hemisphere following the injection of 150 to 250 Tg of smoke. Some of the predicted global consequences of such an injection, together with possible effects from injections of nitrogen oxides and radionuclides, are illustrated in Fig. 6.

The TTAPS study used a global-average model of the atmosphere's vertical structure. These authors estimated that under a hemispheric cloud of about 200 Tg of smoke, land-surface temperatures in midcontinental regions would drop by from 30 to 40°C, from an initial average temperature of about 13°C to temperatures well below freezing. Temperature drops over the oceans were calculated to be small. It was the predicted severe cooling over land that led to the coining of the term "nuclear winter."

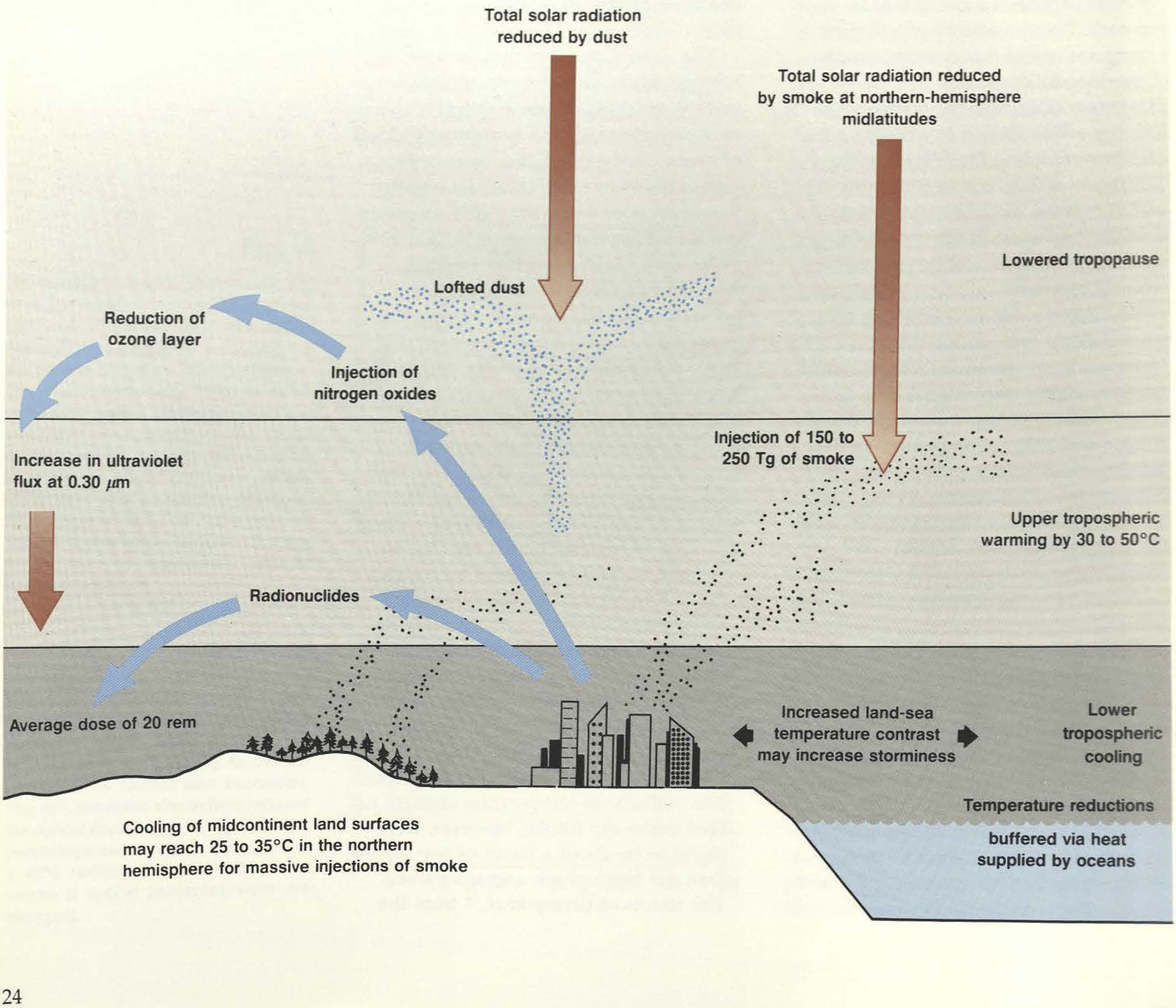
Subsequently, calculations with more detailed models have indicated that substantial cooling may occur over land but may not be so drastic as the TTAPS estimate. The TTAPS estimate of cooling by 40°C in midcontinental regions, for example, should be reduced by roughly one-half to account for the effect of ocean buffering (that is, the modifying effect of warmer ocean air) when considering average temperature changes over land. MacCracken[23] derived an early value of an 8°C hemispheric average temperature reduction over land using a two-dimensional climate model. The midlatitude temperature changes on land under the smoke, however, were found to be about a factor of two greater than the hemispheric average value. The results of Covey *et al.*,[24] from the

Fig. 6

When account is taken of the various assumptions made in early global-effects studies, an injection of about 150 to 250 Tg of smoke into the troposphere would result in cooling of land surfaces by from 25 to 35°C in summer in midcontinental regions of the northern hemisphere. Many of the environmental effects that have been predicted by scientists at LLNL and elsewhere will be modified and refined as the physical uncertainties are further reduced.

National Center for Atmospheric Research, indicated a cooling of about 25°C in summer (and of about 10°C in spring and a few degrees in winter) during the first few weeks after injection of smoke. Their estimates may be somewhat too large because the diurnal cycle, land-surface heat capacity, and the effect of scattering solar radiation were neglected. Soviet estimates of the temperature reduction are somewhat larger but they, in effect, assumed a much larger smoke injection than the other studies.[25] Thus, early studies of the average midlatitude temperature reduction in the northern hemisphere range from about 15 to 25°C when account is taken of the varying assumptions in the models used by these investigators. Predicted midcontinental temperature drops are from 25 to 35°C. The expected biological and ecological effects of this cooling, which is more moderate than suggested by TTAPS, would nonetheless remain significant.

Even this apparent agreement among studies is, however, somewhat deceiving in that all of the climate models included many additional assumptions and simplifications that have not yet been evaluated. For example, none of the models treated the movement of smoke from the scale of individual fires to the global scale. Thus, they did not account for the patchiness of smoke that would be created by the scattered sources,



changing weather, and localized scavenging. Furthermore, none of the models even attempted to relate the removal of smoke to the actual scavenging processes that are operative. These relationships will be especially difficult to model because most precipitation systems are smaller than can be easily resolved in global-climate models. As a result, mesoscale models, which can treat cloud systems with a resolution of several tens of kilometres, must be modified and used to investigate scavenging rates. Finally, many of the assumptions and representations of various processes in the climate models (e.g., the effect of smoke on solar and terrestrial radiation) are not yet accurate enough to ensure that changing a given formulation will not significantly alter the model results.

Three-Dimensional Global-Scale Simulations

Researchers at the Laboratory have recently taken two preliminary steps to address some of the shortcomings in the early climate calculations. The first involves a series of sensitivity studies to evaluate the importance of various assumptions and approximations that were made in early calculations. The second involves the development of significantly improved models that make fewer assumptions.

Our approach has involved the coupling of two models. The first is a two-vertical-layer, three-dimensional, general circulation model (GCM) of the atmosphere that was developed by Oregon State University (OSU). The second is a three-dimensional model of trace species and microphysics called GRANTOUR that is being developed at LLNL. The models are coupled in a fully interactive manner.

In cooperation with scientists from the State University of New York at Stony Brook and from OSU, we have conducted a series of model simulations to assess the sensitivity of the potential climate response to various assumptions. We have tested the sensitivity of the results to assumptions concerning the amount of smoke injected, the altitude distribution of the smoke, the optical properties of the particles, and the manner by which the effect on solar radiation is calculated. For these sensitivity studies, we have assumed that smoke is spread evenly through most of the northern hemisphere and remains fixed, as has been assumed in earlier calculations.

Our results indicate that climatic cooling is greater if the smoke is injected into the upper troposphere rather than into the lowest few kilometres. The increased cooling occurs because absorption of solar radiation takes place above the level where greenhouse gases can trap and then radiate substantial amounts of that energy downward to the surface of the earth.[13]

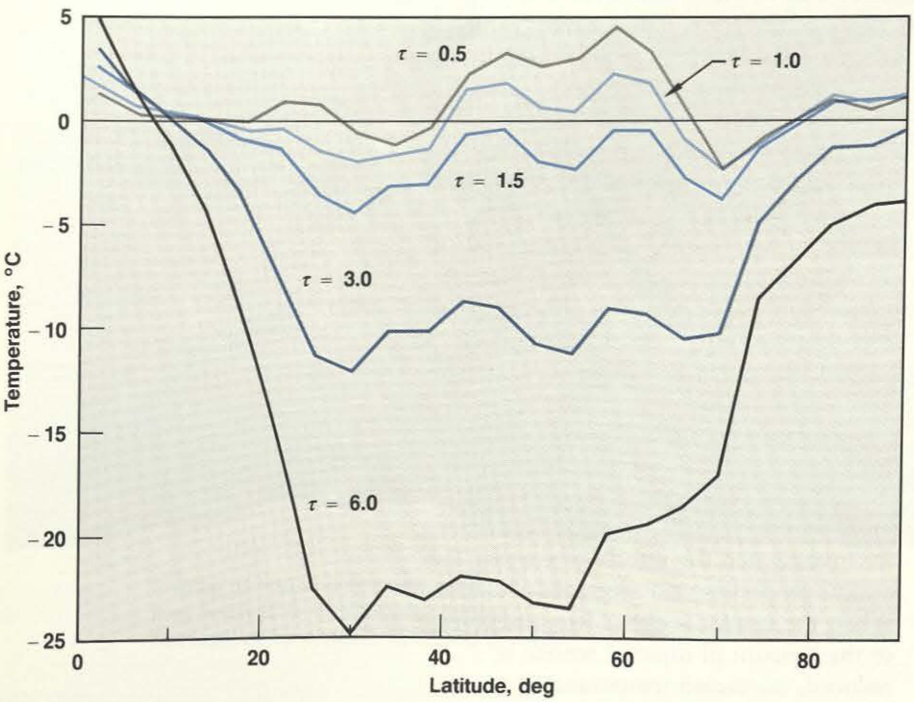
In previous calculations, solar radiation has been treated in a highly simplified manner. The calculations have often assumed either that smoke does not scatter any solar radiation or that scattering can be accounted for by simply reducing the estimated amount of injected smoke. In addition, most calculations have fixed the position of the sun, holding it at an appropriate average angle above the horizon rather than allowing it to follow its normal daily cycle. The first approximation is inaccurate because particles of the size with which we are concerned also tend to scatter solar radiation, with most of it directed downward and toward the surface of the earth. The ultimate effect of such scattering is to reduce the amount of cooling. The second approximation is inaccurate because solar absorption varies exponentially rather than linearly with the amount of smoke along the path of the sun's rays. Thus, significant amounts of solar radiation can reach the surface near noontime through modest amounts of smoke, although little solar radiation reaches the surface when the sun is low on the horizon. Such approximations are particularly important for quantities of smoke that are less than the massive amounts considered in the TTAPS article.

In another series of sensitivity studies, we investigated the effects of varying the optical properties and amounts of smoke. When the smoke is either less absorbing or the amount of injected smoke is reduced, calculated temperature reductions are dramatically decreased. As shown in Fig. 7, if smoke is reduced to about one-third the amount suggested by TTAPS, the hemispheric-scale cooling effect essentially disappears. Such changes in the amount of smoke that might be injected into the atmosphere are well within the current range of uncertainty.

GRANTOUR is a three-dimensional model that can transport smoke particles and estimate the microphysical and scavenging processes that affect their concentration and distribution. To treat these processes more accurately and efficiently, the atmospheric formulation for GRANTOUR is somewhat different than that for our climate model. GRANTOUR divides the troposphere into about 10 000 parcels of equal air mass spread evenly throughout the atmosphere from the surface to 11 km. In the coupled GRANTOUR and GCM model, the parcels are moved by the three-dimensional wind fields calculated by the GCM. The air parcels also carry with them information about the concentration of smoke particles injected into the air mass. Precipitation may occur, depending on what is taking place in the nearest grid cell of the GCM. In general, the GCM portion of the simulation includes treatment of tropospheric dynamics and thermodynamics and of the effect of soot on solar radiation. The GRANTOUR part of the simulation includes treatment of particle transport, microphysics, and scavenging by precipitation.

Fig. 7

Simulation of the expected temperature changes ten days after smoke injections of varying amounts into the northern hemisphere between about 20 and 70 deg north latitude. The different values of optical depth (τ) from top to bottom are approximately equivalent to smoke amounts of 20, 40, 60, 120, and 240 Tg, respectively. The cooling effect becomes negligible for the case of τ = 1.5, which is equivalent to reducing the amount of injected smoke suggested by TTAPS by about 75%. The smoke particles in this simulation absorb 30% of the solar radiation incident upon them. The cooling would be somewhat greater for particles that absorb 50% of the incident solar radiation. Smoke is assumed to be distributed with equal mass-mixing ratios up to about 11 km.



Although our interactive model coupling the GCM with GRANTOUR treats some new processes, it still has many limitations. Perhaps the most important problem in conducting global-scale simulations is the development of more accurate algorithms for representing the scavenging process. This is a particularly difficult problem because actual precipitation occurs on scales that are smaller than the parcels treated by the climate model. Furthermore, there are no simple ways to verify that the approximation is working properly.

At present, we relate the scavenging rate for smoke to the removal rate of water vapor in the atmosphere. The particle lifetime, based on rates of evaporation and precipitation, is a little more than a week in the normal atmosphere. We follow two classes of smoke particles: those with diameters less than 1 μm and those with diameters of 1 μm and larger. With our assumptions, the larger smoke particles are removed a few times more rapidly than the water vapor because of the many processes that can remove large particles in a cloud. Smaller particles (less than 1 μm in diameter) are removed somewhat less rapidly than water vapor because such particles tend, in ways not clearly understood by microphysicists, to avoid capture. Testing and verification of these approximations is the subject of current research.

At present, for these simulations, we assume that the optical characteristics of smoke particles remain constant in time, an assumption that may overestimate optical depth as particles coagulate. Another important limitation of the simulation is that the resolution of the 10 000 parcels in the GRANTOUR model is only adequate to treat scales on the order of a few hundred kilometres on a side. Finally, we do not treat the possibility that the smoke could be heated and rise into the stratosphere; our newest version will include this.

Our most recent studies prescribe solar declination at its July value. July was selected for our calculations because it appears to be one of the most sensitive months in terms of the potential climatic effects of smoke. As expected, the resulting predicted conditions over land for the normal climate unperturbed by smoke are somewhat warmer than would actually be observed during July because the model assumes that solar conditions for July have persisted indefinitely. This extended period of July solar radiation also tends to dry out the continents and results in somewhat less precipitation than is actually observed. For the period we are now studying, the first month or so after the injection of smoke exchange, we do not allow the temperature of the ocean to change from its observed July values. Although changes in ocean temperature are probably not important during the first few weeks, they may become significant as we begin to study longer periods.

Thus, despite our many improvements, care must be taken in interpreting our results because the present necessary approximations and assumptions may affect the outcomes of the interactive model in ways that are not yet well understood. At this stage, results from models at LLNL and elsewhere should still be viewed not so much as predictions of what will happen but, rather, as sensitivity studies of what processes are important in determining the potential climatic perturbation of large amounts of smoke in the atmosphere.

Transport and Distribution of Smoke

For the simulations we have run to date, our basic reference calculation assumes an injection of 150 Tg of smoke into the troposphere.[26] This amount of smoke is equivalent to the TTAPS[4] and Academy[6] estimates for urban fire emissions in their baseline scenarios.

We have neglected any smoke from forest fires. TTAPS assumed 80 Tg and the Academy report assumed 30 Tg from this source. As previously discussed, recent studies suggest that the amount of such smoke is likely to be much less than the urban smoke, that it is a poorer absorber than urban smoke, that it would be injected at lower altitudes, and that it is thus expected to affect the climate much less than urban smoke.

We refer to the 150-Tg simulation as an interactive calculation because the smoke is moved through the atmosphere by winds and can be scavenged by precipitation. The smoke, in turn, alters the radiation distribution in the atmosphere and thus the calculated climatic conditions. Our analyses have focused on the pattern of spreading smoke and on the resulting changes in surface temperatures.

Figure 8 shows the distribution of smoke on several days after a nuclear exchange from a vantage point centered approximately over the mid-Atlantic Ocean. Each dot represents about 4000 tonnes of smoke spread throughout a volume of 550 000 km^3. The smoke is injected at five locations: the western U.S., the eastern U.S., Europe, and two areas in the Soviet Union. This distribution of sites does not come from a detailed war scenario but simply places the emissions where very large numbers of major fires seem plausible.

During the first day (Fig. 8a), the smoke has not spread much beyond the source regions. Thus, we can immediately appreciate the substantial departure from previous models that assume an instantaneous and uniform distribution of smoke throughout the northern hemisphere.[4,6,23,24] The maximum optical depths over Europe and Asia are as large as 50 at this time. Somewhat more rapid dispersion by stronger winds over North America yields maximum optical depths of about 20. Although many water clouds have optical depths of ten or more, light is still able to pass through because the cloud droplets scatter rather than absorb the solar radiation. For smoke from urban fires, once optical depths reach three to five, virtually no solar radiation would reach the surface at average angles of solar elevation. If this smoke were spread uniformly over the hemisphere, the average optical depth would be about three (roughly equivalent to the TTAPS estimate for a similar case).

By the fifth day (Fig. 8b), easterly winds in this meteorological simulation have carried smoke from western North America toward the southwest. Smoke from eastern North America has been carried across the Atlantic Ocean, and Eurasian smoke has swept across Asia toward the Pacific Ocean. Maximum optical depths have decreased to below 20; however, the average northern-

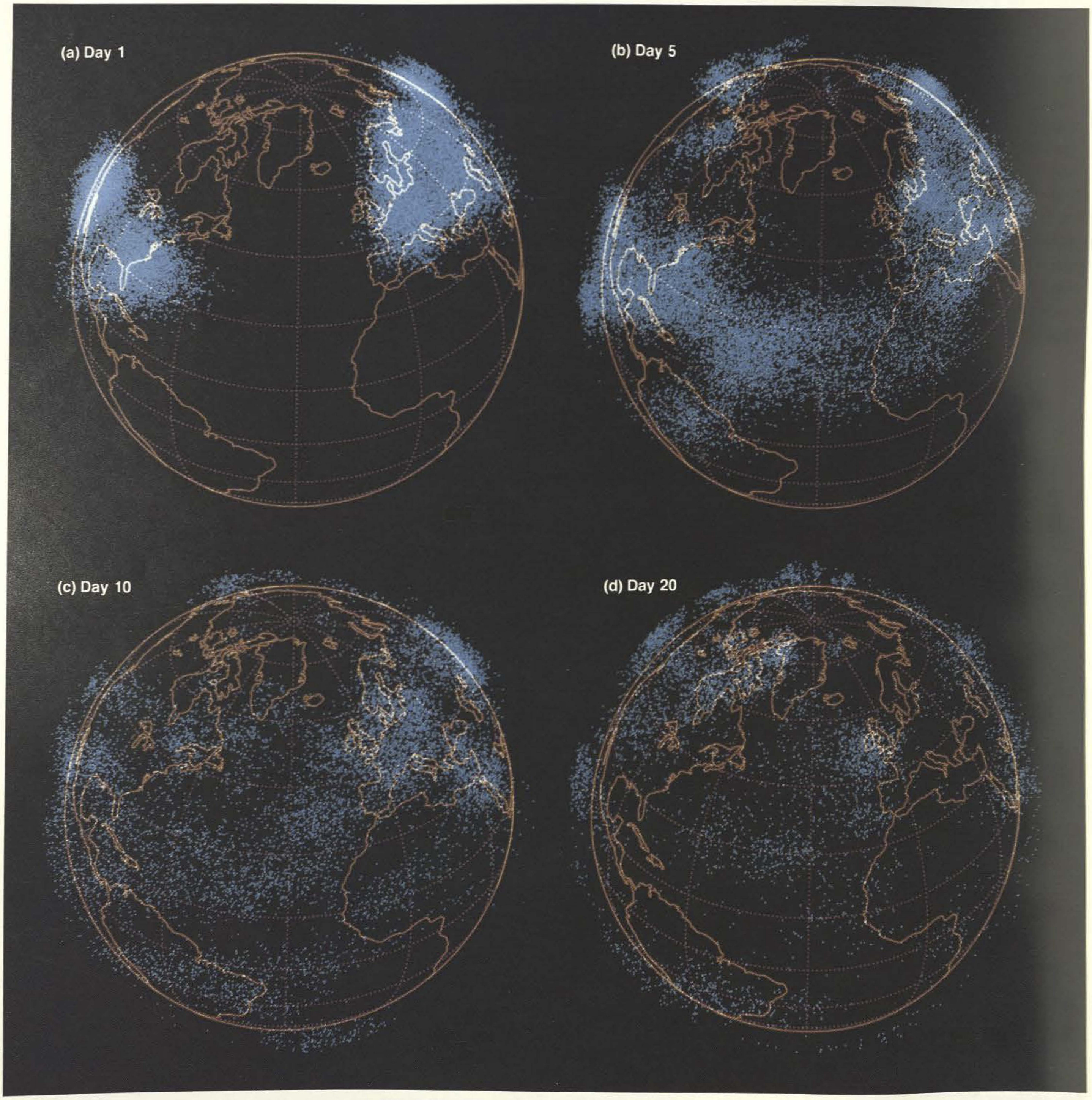


Fig. 8

GCM-GRANTOUR simulation of smoke distribution following an initial injection of 150 Tg of smoke. Each dot in (a) represents about 4000 tonnes of smoke spread throughout a volume of 550 000 km^3 (about 450 by 450 by 3 km) on the first day of an exchange. Patchiness continues to be evident on the fifth day (b) and the tenth day (c). By the twentieth day (d), smoke spreads more uniformly over the northern hemisphere except in low latitudes. Some smoke also spreads to equatorial and subtropical latitudes of the southern hemisphere.

hemispheric optical depth remains about the same as on the first day because scavenging is quite slow for the small smoke particles that are important in determining optical depth.

Patchiness persists throughout the calculation and is quite evident even on the tenth day (Fig. 8c). We may actually be underestimating patchiness because of our approximations in calculating the scavenging process. The GCM assumes that rain occurs uniformly over a relatively large area, whereas, in fact, heavy rainfall tends to occur in more localized regions. Thus, greater patchiness may be expected after we refine the model to include more discrete regions of varying precipitation. This is an important issue because smoke particles absorb light exponentially. The total hemispheric absorption of solar radiation (and therefore the change in hemispheric average temperature) would decrease as patchiness increases.

By the twentieth day (Fig. 8d), the smoke has spread more uniformly over the northern hemisphere, except in low latitudes. Maximum optical depths are reduced to ten. The average optical depth over the northern hemisphere is about two, indicating some scavenging of smoke and also some spread of the smoke to equatorial and subtropical latitudes of the southern hemisphere by wind changes induced by the smoke.

Another way to view the results of the same 150-Tg interactive simulation is to display concentrations of smoke in three different layers of the atmosphere. Figure 9 shows results for the tenth day.

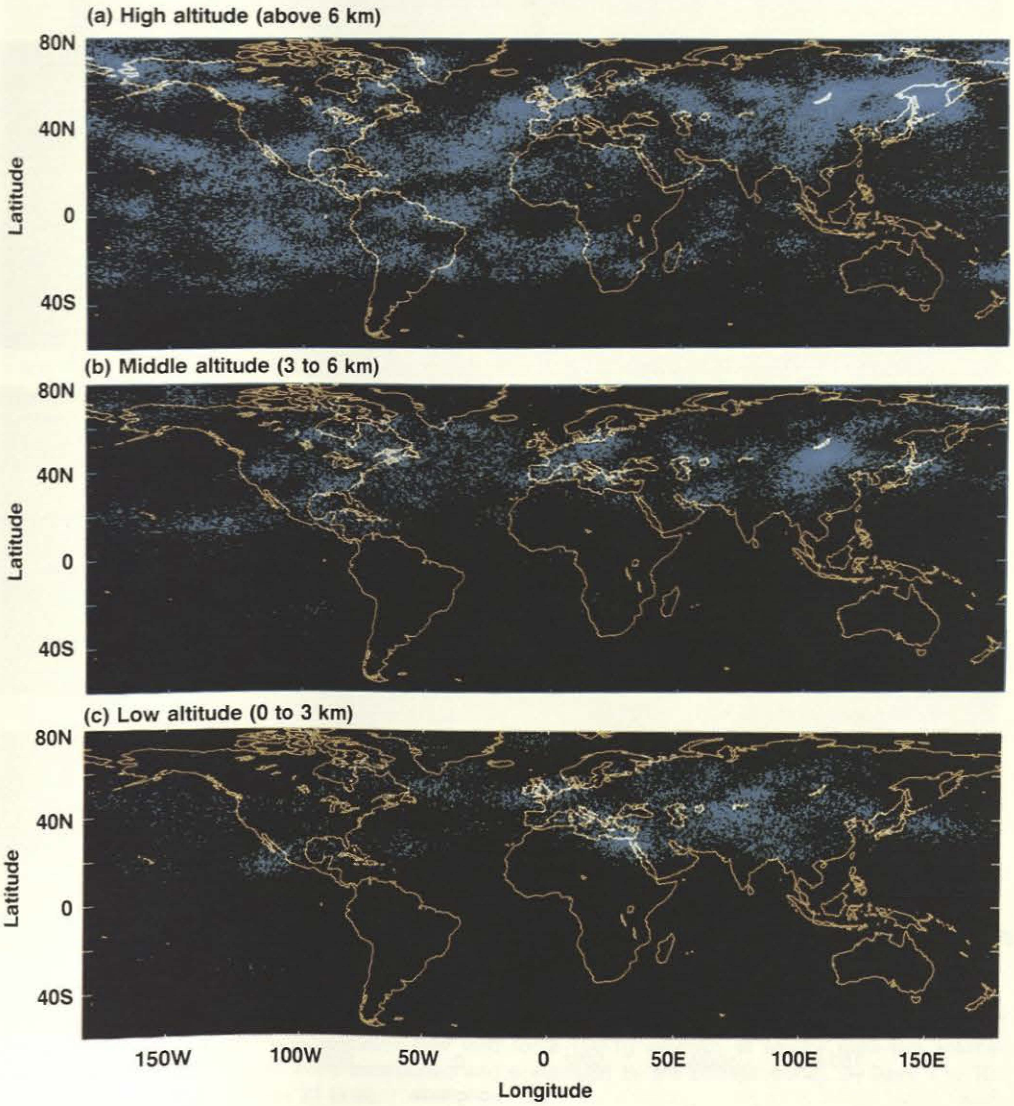


Fig. 9

Vertical distribution of smoke on the tenth day after an injection of 150 Tg. This coupled GCM–GRANTOUR calculation is an interactive simulation for moving smoke. The smoke is patchy and somewhat denser in the uppermost layer of the troposphere.

The lowest layer, shown in Fig. 9c, extends from the surface to an altitude of 3 km, the intermediate layer (Fig. 9b) extends from 3 to 6 km, and the highest tropospheric layer (Fig. 9a) extends from 6 to 11 km. Again, each dot represents a mass of about 4000 tonnes of smoke. We have assumed that the smoke is initially injected about equally, in terms of mass, in each of the three layers.

By the thirtieth day (Fig. 10), concentrations of smoke are reduced most in the lowest layer of the atmosphere because of dispersion and scavenging by precipitation. The smoke has also spread into the southern hemisphere, particularly in the upper layers where winds are stronger. Such smoke could affect land temperatures in the southern hemisphere.

Temperature Response

The calculated pattern of temperature change over time for our assumed injection of 150 Tg of smoke is depicted in Fig. 11. For days 1 to 10 (Fig. 11a), average temperature decreases on land surfaces beneath dense smoke are as large as 20°C, for example, over midcontinental Asia. Regions experiencing little or no smoke over this period, such as China and southern Asia, experience virtually no temperature change. For days 11 to 20 (Fig. 11b), the average temperature decreases by as much as 35°C over Asia. In contrast, the temperature change over North America is far less than in Asia because the winds in this particular simulation have carried much of the smoke off the continent and replaced the smoke with clean Pacific air.

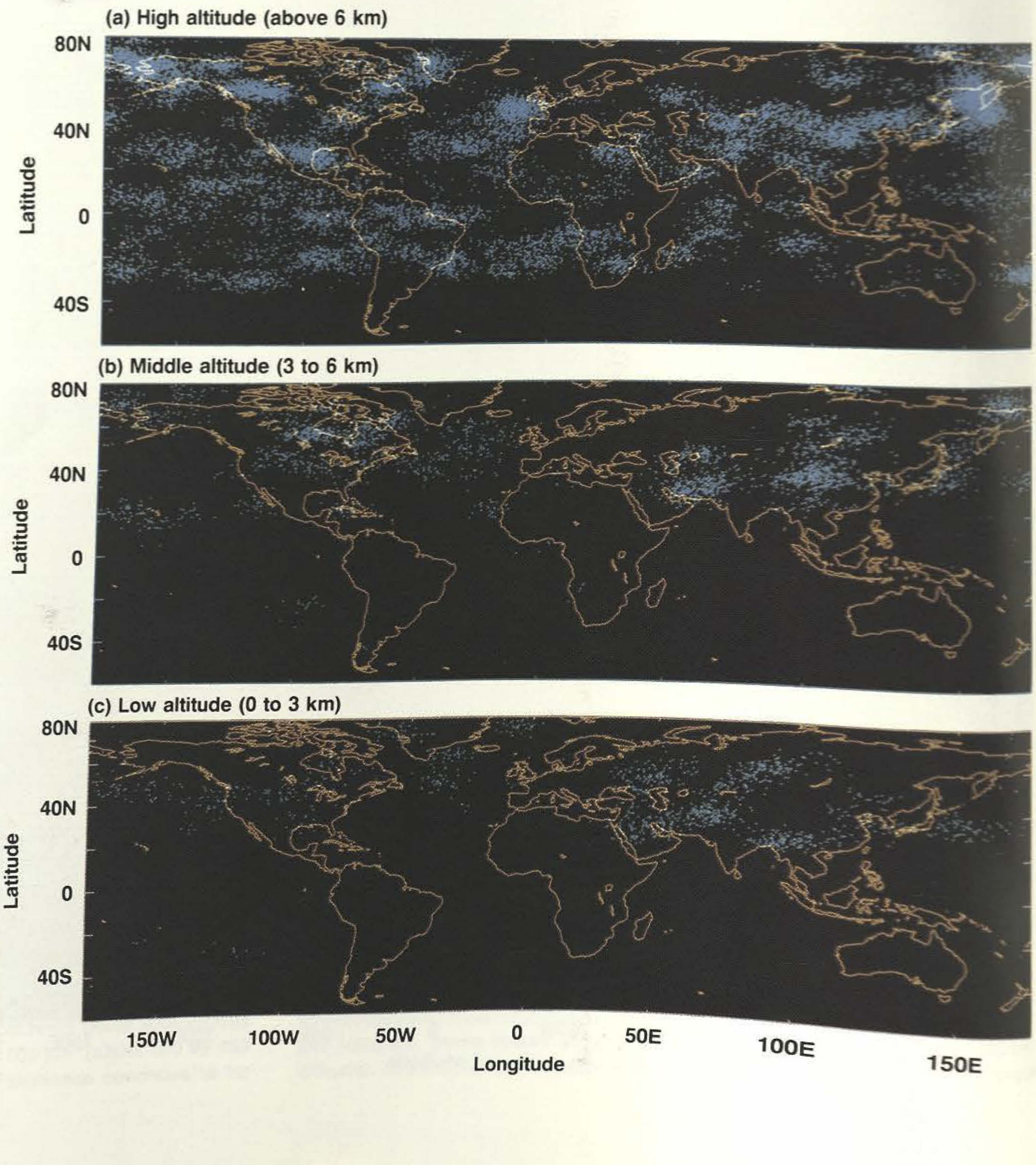


Fig. 10

Vertical distribution of smoke for the thirtieth day after an injection of 150 Tg. In this coupled GCM-GRANTOUR interactive calculation, concentrations of smoke are entering the upper atmosphere and are reduced more in the lower layer of the troposphere because of dispersion and scavenging by precipitation.

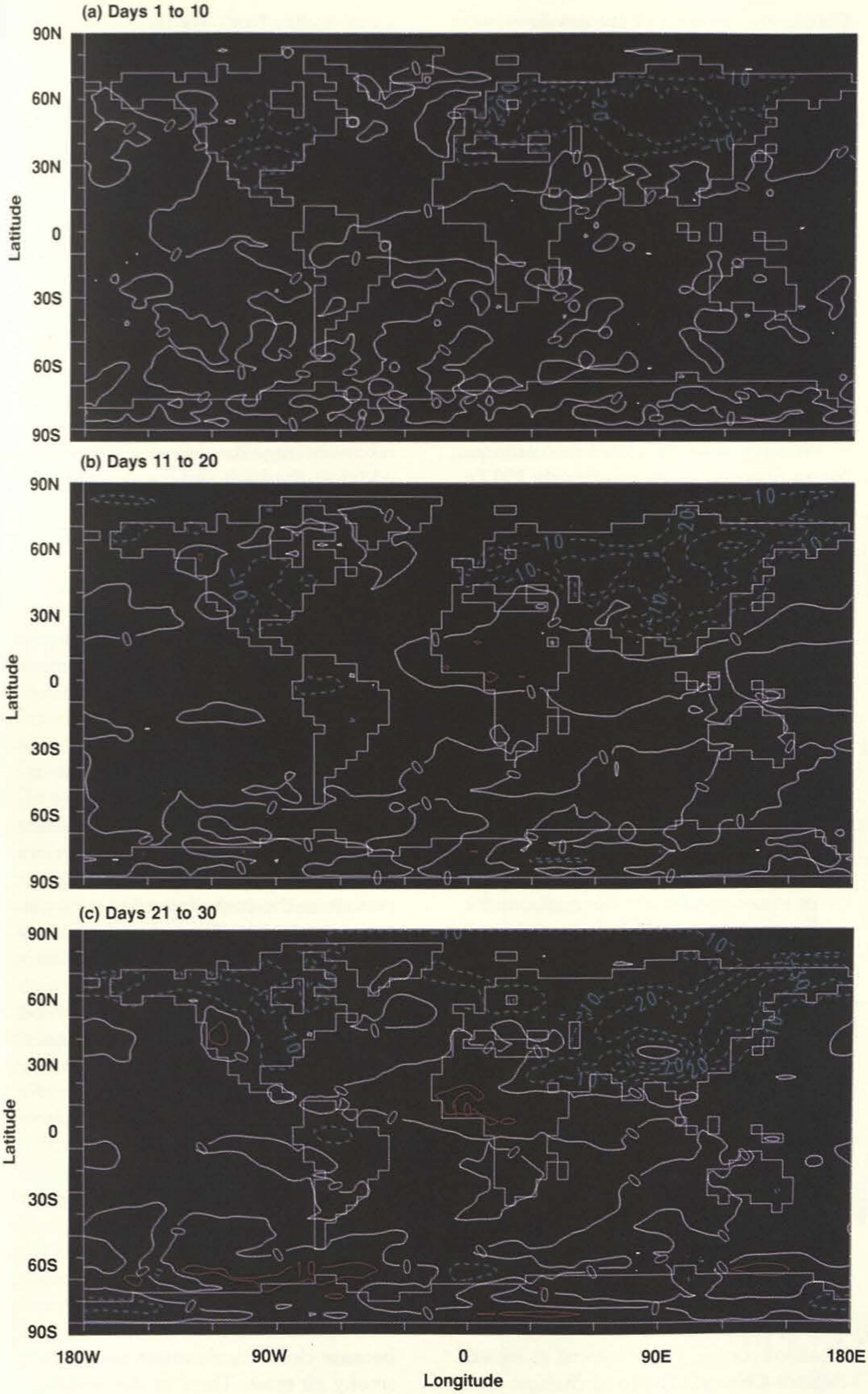


Fig. 11

Average changes in surface temperature over land for a 150-Tg injection of smoke from five source regions. The smoke is interactively transported and scavenged by the climate model. (a) Days 1 to 10, (b) days 11 to 20, and (c) days 21 to 30.

Clearly, the location of the smoke determines where the temperature changes will occur. In addition, ocean buffering (the heating effect over land by air that has been warmed over the oceans) is greater for North America than for the larger continent of Asia. From days 21 to 30 (Fig. 11c), the cooling begins to moderate in the northern hemisphere by a few degrees as some of the smoke is carried to the southern hemisphere. Only modest cooling occurs in the southern hemisphere for our July simulation, cooling that is by no means as extreme as the quick freezes suggested by Covey *et al.*[24]

We have also completed calculations for an injection of approximately 150 Tg of smoke, assuming that it is immediately spread uniformly around the northern hemisphere and then held fixed in time and space. The purpose of such calculations is to isolate the effect of moving smoke. We refer to these simulations as "uniform-smoke" calculations. As expected, patchy smoke in the interactive case causes more extreme temperature reductions under regions of dense smoke and less change elsewhere than for the uniform-smoke calculations. These differences are greatest during the first ten days. After a few weeks, the moving smoke spreads to cover almost uniformly the midlatitudes of the northern hemisphere, and there is relatively little difference between our interactive and uniform-smoke calculations.

We have also made calculations assuming only 10% as much smoke is injected. Once the smoke is spread uniformly, injection of 15 Tg of smoke causes virtually no significant temperature changes; in fact, a little warming may even arise from a slightly reduced planetary albedo because the dark smoke is less reflective than either clouds or some parts of the earth's surface. At early times, however, the dense patches can induce modest and localized cooling (from several to tens of degrees Celsius). The local changes are, of course, not as large as those following a 150-Tg injection.

To gain some perspective on the general character of predicted changes on a day-to-day basis, we have also plotted the predicted temperature variations over time at two particular locations. Such numerical results should be viewed only in terms of their general features and not as quantitative estimates or projections. Figure 12a shows temperature changes for a location in the central U.S. for a case with both interactive and uniformly spread smoke (about 150 Tg) and compares these two outcomes with our control simulation which has no smoke. The effects are representative of a dry agricultural area in summer. It is evident that the normal daily temperature cycle in the absence of smoke involves relatively large day-to-night variations. In addition, the high and low temperatures over the month are not constant; rather, cooler and warmer periods appear as different weather systems move across the midcontinental U.S.

For the simulation assuming a uniformly spread smoke (optical depth of three at this latitude), less than about one-quarter of the normal light reaches the earth's surface. The diurnal temperature cycle continues to be evident, although the daily variation is not as large as that for the control simulation. While the temperatures do decrease, resulting temperatures are not substantially cooler than the normal cool periods in the control simulation (without smoke). Thus, maximum daily temperatures with uniform smoke are not much cooler than minimum temperatures when no smoke is present. While such changes may affect crops, they are not immediately life-threatening.

Outcomes for a 150-Tg injection of moving smoke differ substantially from those for uniformly spread smoke. The smoke is initially so thick over the central U.S. that virtually no sunlight reaches the surface. Temperatures decrease rapidly and the diurnal temperature cycle disappears. Following the period of sharp cooling, temperatures recover to near normal for a short time because clean Pacific air replaces the smoky air mass. Then, as the smoke continues to spread, other patches induce periods of cooling. After thirty days, when the smoke has spread more or less uniformly over the hemisphere, surface temperature reductions for the two simulations with smoke are similar.

The pattern of temperature variation for a location over western Asia (Fig. 12b) is similar in character to that for North America. However, because Asia is a larger continent and the effects of ocean buffering of the temperature change are less effective, the cooling is more severe. Uniform smoke induces a gradual but steady temperature decrease to about 20 to 25°C below the control simulation. For moving smoke, the diurnal cycle completely disappears, indicating that virtually no sunlight is reaching the surface. A very sharp drop in temperature occurs in the first few days and persists until the smoke spreads more evenly over the hemisphere. The control temperatures in our perpetual-July simulation for western Asia (about 35 to 40°C) are warmer than the observed temperatures during an average summer; the present calculations may be slightly underestimating the intensity and duration of subfreezing temperatures. Future calculations, which will include seasonal variations, should more accurately treat this effect.

In general, our interactive simulations predict relatively large decreases in surface temperatures for several geographical regions. Because these sharp temperature drops start from summer rather than global-average conditions, however, we do not find indications of the extended deep freeze predicted by TTAPS. The temperature changes may also be quite variable as smoke intensity varies. Such variability makes assessment of potential biological and ecological consequences much more difficult than if a simple decrease to temperatures well below 0°C were to occur, as the TTAPS report suggested. We do not expect the potential atmospheric and environmental effects to become significantly less serious as model simulations become more complete unless the amount of injected smoke is reduced several-fold.

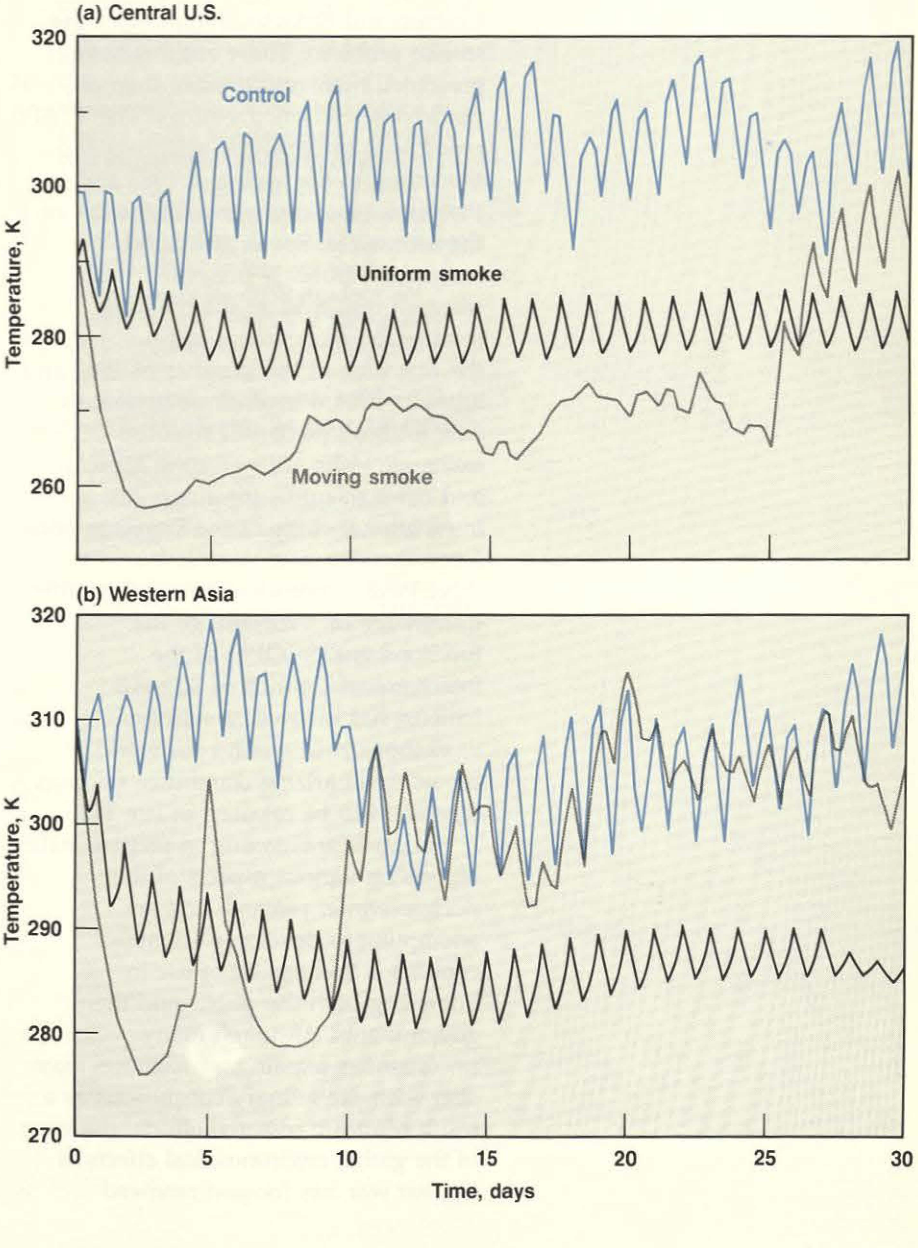
Future Cooperative Research

Many calculations now indicate that significant cooling would occur if massive amounts of smoke from burning urban areas were injected high into the atmosphere during the warm season. The possibility of the cooling effect identified by Turco and his colleagues has now been confirmed by a number of researchers and is further supported in a review recently published by the National Academy of Sciences.[6] Considerably more effort is required, however, to understand whether substantial cooling is likely or is a remote possibility.

Recognizing the implications of this effect, the DNA and the Department of Energy have established research programs to investigate the problems

Fig. 12

Temperature changes over a thirty-day period for (a) the central U.S. and (b) western Asia. The calculations for moving and uniformly spread smoke (150 Tg of injected smoke) can be compared with the control simulation (no smoke). The cooling effects of smoke are more severe in Asia than in the U.S. because Asia is a larger continent and the influence of ocean buffering is reduced. For the interactive calculation with moving smoke, the diurnal cycle that is apparent throughout the control simulation and the uniform-smoke case initially disappears, and a sharp drop in temperatures occurs until the initial dense smoke cover thins as the smoke spreads out over the hemisphere.



further. In addition, the National Climate Program Office has coordinated development of a research plan that outlines additional necessary research.[7] The major recommendations of this plan are for measurements of the characteristics of smoke emissions from fires of various sizes and greatly increased efforts to model atmospheric effects on the mesoscale and the global scale.

Another approach to advancing our understanding of the issues has been the convening of scientific meetings and workshops to discuss progress and to help identify and resolve uncertainties. The Royal Swedish Academy of Sciences sponsored the 1982 study that led Crutzen and Birks to first quantify the smoke problem. These authors have presented their results since then at numerous scientific meetings. The TTAPS report was presented to scientists at a workshop in the spring of 1983 and to the public at a conference in the fall of the same year. Soviet and LLNL researchers publicly presented their research results at an international seminar on nuclear war in Erice, Italy, for the first time in the summer of 1983 and again in 1984. We continue to discuss new findings as part of scientist-exchange visits at Livermore, Moscow, and other scientific meetings. An international study of the Environmental Consequences of a Nuclear War (ENUWAR), sponsored by the Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions, has involved a series of workshops held around the world. A report summarizing committee findings is scheduled to be released in late 1985.

Scientists are starting to prepare status reports on various aspects of their nuclear-winter research and are attempting to develop a scientific consensus that can be of use in informing both the public and their governments. Although many uncertainties remain and scientists may alter their preliminary conclusions as a result of future research efforts, the issue of the global environmental effects of nuclear war has focused renewed attention on the need for all nations to strive for greater global stability and enduring peace. ■

Key Words: atmosphere—modeling, stratosphere, tropopause, troposphere; climate—global, induced cooling; computer code—general circulation model (GCM), GRANTOUR; fallout; fires—energy-release rate, forest, nuclear-generated, urban; nuclear—exchange, scenario, war, winter; ozone; radiation—infrared, nuclear, solar, ultraviolet; rainout; smoke—coagulation, condensation, microphysics, optical properties, particles, plume, radiative properties, scavenging, spreading.

Notes and References

1. *Long-Term Worldwide Effects of Multiple Nuclear-Weapon Detonations,* National Academy of Sciences (National Academy Press, Washington, D.C., 1975).
2. M. C. MacCracken and J. S. Chang, Eds. *A Preliminary Study of the Potential Chemical and Climate Effects of Atmospheric Explosions,* Lawrence Livermore National Laboratory, Livermore, California, Rept. UCRL-51653 (1975).
3. P. J. Crutzen and J. W. Birks, "The Atmosphere After a Nuclear War: Twilight at Noon," *Ambio* **11**, 114 (1982).
4. R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, and C. Sagan, "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," *Science* **222** (4630), 1283–1292 (1983).
5. P. R. Ehrlich *et al.,* "Long-Term Biological Consequences of Nuclear War," *Science* **222** (4630), 1293–1300 (1983).
6. *The Effects on the Atmosphere of a Major Nuclear Exchange,* National Academy of Sciences (National Academy Press, Washington, D.C., 1985).
7. *Interagency Research Report for Assessing Climatic Effects of Nuclear War,* Report to the Office of Science Technology and Policy, prepared by The National Climate Program Office, National Oceanic and Atmospheric Administration (February 5, 1985).
8. C. R. Molenkamp, *Numerical Simulation of Self-Induced Rainout Using a Dynamic Convective Cloud Model,* Lawrence Livermore National Laboratory, Livermore, California, Rept. UCRL-83583 (1980).
9. J. B. Knox, "Global Deposition of Radioactivity from a Large-Scale Exchange," *Intl. Conf. Nuclear War, 3rd,* Erice, Italy (1983); also available as Lawrence Livermore National Laboratory Rept. UCRL-89907 (1983).
10. Several recent studies have also projected that ozone reduction may result from chlorocarbon releases from aerosol spray cans and other sources. For the relatively small but longer-lasting ozone depletion brought about this

way, the health concern is with the long-term, integrated ultraviolet dose, which has been related to some kinds of skin cancer.

11. J. E. Penner, "Tropospheric Response to a Nuclear Exchange," *Intl. Conf. Nuc. War, 3rd,* Erice, Italy (1983); also available as Lawrence Livermore National Laboratory Rept. UCRL-89956 (1983).
12. H. Stommel and E. Stommel, "The Year Without a Summer," *Sci. Amer.* **240**, 176 (1979).
13. The energy fluxes to and from the earth's surface, atmosphere, and space are discussed in *Energy and Technology Review* (UCRL-52000-84-9), September 1984, p. 11.
14. R. D. Small and B. W. Bush, "Smoke Production from Multiple Nuclear Explosions in Non-Urban Areas," *Science* (1985), in press.
15. Resumé of Discussions and Conclusions at the SCOPE-ENUWAR Workshop, Paris, 22–24 October 1984, Scientific Committee on Problems of the Environment (1984).
16. See for example, G. E. Carrier, F. E. Fendell, and P. S. Feldman, "Firestorms," *Fire Dynam. Heat Transfer* **25**, 55–64 (1983). These authors modified a semianalytic approach developed to describe the dynamics of small-scale fires by B. R. Morton, G. Taylor, and J. S. Turner, "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," *Proc. Roy. Soc. London,* Series A **234**, 1–23 (1956). To match the predictions reported from the Hamburg firestorm, Carrier *et al.* assumed that the mixing of hot plume air and cool background air was restricted far more than is actually observed in less intense fires.
17. P. C. Manins, "Cloud Heights and Stratospheric Injections Resulting from a Thermonuclear War," *CSIRO* Division of Atmospheric Research, Mordialloc, Australia (1984); Manins used the theory of Morton *et al.*, noted in Ref. 16, directly but treated fires as point sources.
18. J. E. Penner, L. C. Haselman, and L. L. Edwards, "Buoyant Plume Calculations," *AIAA Aerospace Sci. Meeting, 23rd,* Reno, Nevada (1985); also available as Lawrence Livermore National Laboratory Rept. UCRL-90915 (1985).
19. W. R. Cotton, "Atmospheric Convection and Nuclear Winter," *Amer. Sci.* **73** (1985), in press.
20. V. Ramaswamy and J. T. Kiehl, "Sensitivities of the Radiative Forcing Due to Large Loadings of Smoke and Dust," *J. Geophys. Res.* **90** (1985), in press.
21. F. Luther, "Uncertainties of Radiative Properties of Smoke and Their Effect on Climate Assessments," *Proc. Intl. Sem. Nuclear War, 4th,* Erice, Italy (1984).
22. J. E. Penner, "Smoke Inputs to Climate Models: Optical Properties and Height Distribution for Nuclear Winter Studies," *Proc. Intl. Sem. Nuclear War, 4th,* Erice, Italy (1984).
23. M. C. MacCracken, "Nuclear War: Preliminary Estimates of the Climatic Effects of a Nuclear Exchange," *Proc. Intl. Sem. Nuclear War, 3rd,* Erice, Italy (1983).
24. C. Covey, S. H. Schneider, and S. L. Thompson, "Global Atmospheric Effects of Massive Smoke Injections from a Nuclear War: Results from General Circulation Model Simulations," *Nature* **308**, 21–25 (1984).
25. V. V. Aleksandrov and G. L. Stenchikov, "On the Modeling of the Climatic Consequences of Nuclear War," in *Proc. on Applied Mathematics of the USSR Academy of Science,* Moscow (1983); V. V. Aleksandrov and G. L. Stenchikov, "On a Computational Experiment Modeling the Climatic Consequences of Nuclear War," *J. Computat. Math. and Math. Phys.* **14**, No. 1, 140 (1984) (in Russian).
26. M. C. MacCracken and J. J. Walton, *The Effects of Interactive Transport and Scavenging of Smoke on the Calculated Temperature Change Resulting from Large Amounts of Smoke,* Lawrence Livermore National Laboratory, Rept. UCRL-91446 (1984).