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# The Climatic Effects of Nuclear War

*New findings tend to support the view that the immense clouds of smoke and dust raised by even a medium-scale nuclear war could bring about a global "nuclear winter"*

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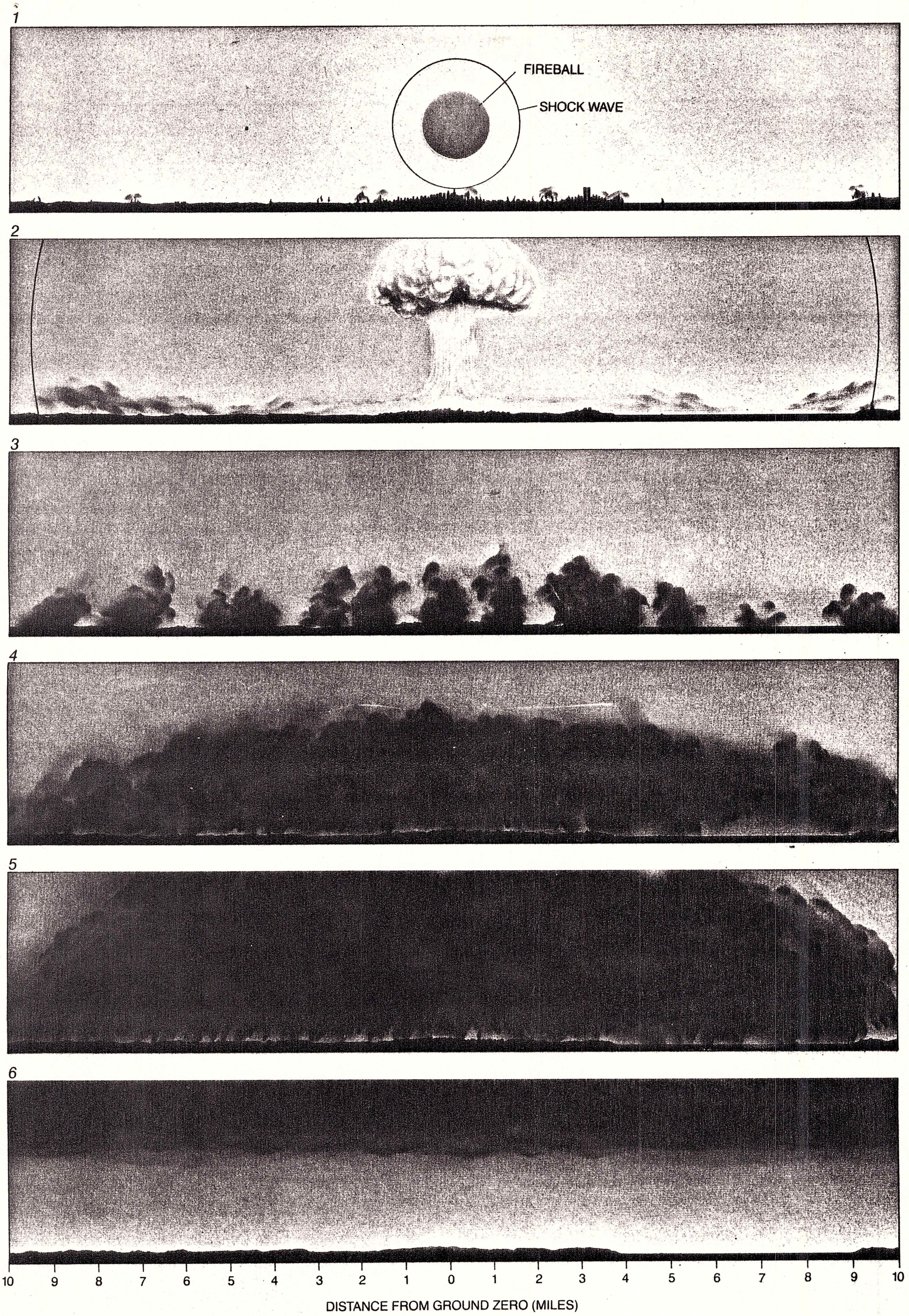
Since the beginning of the nuclear arms race four decades ago it has been generally assumed that the most devastating consequence of a major nuclear war between the U.S. and the U.S.S.R. would be a gigantic number of human casualties in the principal target zones of the Northern Hemisphere. Although in the wake of such a war the social and economic structure of the combatant nations would presumably collapse, it has been argued that most of the noncombatant nations—and hence the majority of the human population—would not be endangered, either directly or indirectly. Over the years questions have been raised about the possible global extent of various indirect, long-term effects of nuclear war, such as delayed radioactive fallout, depletion of the protective ozone layer in the upper atmosphere and adverse changes in the climate. Until recently, however, the few authoritative studies available on these added threats have tended to play down their significance, in some cases emphasizing the uncertainty inherent in any attempt to predict the combined effects of multiple nuclear explosions.

This comparatively optimistic view of the potential global impact of nuclear war may now have to be revised. Recent findings by our group, confirmed by workers in Europe, the U.S. and the U.S.S.R., suggest that the long-term climatic effects of a major nuclear war are likely to be much severer and farther-reaching than had been supposed. In the aftermath of such a war vast areas of the earth could be subjected to prolonged darkness, abnormally low temperatures, violent windstorms, toxic smog and persistent radioactive fallout—in short, the combination of conditions that has come to be known as "nuclear winter." The physical effects of nuclear war would be compounded by the widespread breakdown of transportation systems, power grids, agricultural production, food processing, medical care, sanitation, civil services and central government. Even in regions far from the conflict the survivors would be imperiled by starvation, hypothermia, radiation sickness, weakening of the human immune system, epidemics and other dire consequences. Under some circumstances, a number of biologists and ecologists contend, the extinction of many species of organisms—including the human species—is a real possibility.

Our own involvement in the reassessment of the global effects of nuclear war originated in a confluence of several lines of inquiry. Before joining forces we had separately and collectively been engaged in research on such phenomena as dust storms on Mars and the climatic effects of explosive volcanic eruptions on the earth; more recently we all became interested in the hypothesis that one or more of the mass extinctions of species evident in the geologic record were caused by immense clouds of dust raised by the impact of an asteroid or a comet. In 1982 a committee of the National Academy of Sciences, recognizing the parallels between the dust raised by nuclear explosions and that raised by other cataclysmic events, such as volcanic eruptions and meteorite impacts, asked us to look into the possible climatic effects of the dust likely to result from a nuclear war. We had already been considering the question, and to address it further we had at our disposal sophisticated computer models of both large- and small-scale atmospheric phenomena; the models had been developed over the preceding decade primarily to study the origins, properties and effects of particles in the atmosphere.

At about the same time another important aspect of the question came to our attention. An article in the Swedish environmental journal *Ambio*, coauthored by Paul J. Crutzen of the Max Planck Institute for Chemistry at Mainz in West Germany and John W. Birks of the University of Colorado at Boulder, pointed out that fires ignited by nuclear explosions could generate massive amounts of smoke, severely attenuating the sunlight reaching the ground. Accordingly we added smoke to dust as a likely perturbing influence of nuclear war on the climate.

In brief, our initial results, published in *Science* in December, 1983, showed that "the potential global atmospheric and climatic consequences of nuclear war... are serious. Significant hemispherical attenuation of the solar radiation flux and subfreezing land temperatures may be caused by fine dust raised in high-yield nuclear surface bursts and by smoke from city and forest fires ignited by airbursts of all yields." Moreover, we found that long-term exposure to nuclear radiation from the radioactive fallout of a nuclear war in the Northern Hemisphere could be an order of magnitude greater than previous studies had indicated; the radioactivity, like the other nuclear-winter effects, could even extend deep into the Southern Hemisphere. "When combined with the prompt destruction from nuclear blast, fires and fallout and the later enhancement of solar ultraviolet radiation due to ozone depletion," we concluded, "long-term exposure to cold, dark and radioactivity could pose a serious threat to human survivors and to other species." Subsequent studies, based on more powerful models of the general circulation of the earth's atmosphere, have tended to confirm both the validity


1
FIREBALL
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DISTANCE FROM GROUND ZERO (MILES)

of our investigative approach and the main thrust of our findings. In what follows we shall review the current state of knowledge on this vital issue.

Before one can understand the climatic effects of nuclear war one must first understand how the earth's radiation budget is normally balanced. The amount of sunlight absorbed by the atmosphere and the surface of the earth, averaged over time, is equal to the amount of thermal radiation emitted back into space. Because the intensity of the thermal radiation varies as the fourth power of the temperature, both the surface temperature and the atmospheric temperature can adjust fairly quickly to maintain the overall energy balance between the solar energy gained and the thermal energy lost.

If the earth were an airless body like the moon, its surface would radiate the absorbed solar energy directly into space. In this case the globally averaged temperature of the earth would be well below the freezing point of water, and life as we know it could not exist on our planet. Fortunately the earth has an atmosphere, which absorbs and traps some of the heat emitted by the surface, thereby raising the average ground-level temperature to well above freezing and providing a favorable environment for forms of life, such as ours, that are based on liquid water.

The thermal insulation of the earth's surface by the atmosphere—the "greenhouse effect"—arises from the fact that sunlight passes through the atmosphere more readily than thermal radiation does. The radiation emitted by the sun is mainly in the visible part of the electromagnetic spectrum, whereas the thermal radiation emitted by the earth's surface is concentrated in the infrared part. The main infrared-absorbing components of the atmosphere are water (in the form of ice crystals, liquid droplets and vapor) and carbon dioxide gas, both of which are essentially transparent to visible light. Hence the atmosphere generally acts as a window for sunlight but as a blanket for heat.

Under normal conditions the temperature of the troposphere, or lower atmosphere, decreases gradually with increasing altitude up to a height of about 12 kilometers, the boundary called the tropopause. Heat from the earth's surface is transferred upward through the atmosphere by several mechanisms: thermal radiation, small-scale turbulence, large-scale convection and the release of latent heat through the condensation of ascending water vapor. In a purely radiative atmosphere (that is, one in which the air does not move vertically and all the energy is transferred by radiation) the lower layers of air, where most of the solar energy is absorbed, would be warmer than the higher layers; in this situation the upward thermal radiation would exceed the downward thermal radiation, allowing the excess heat to escape into space. If the opacity of the atmosphere to infrared radiation were to increase (with no change in the opacity to visible light), the temperature would increase. For example, if carbon dioxide, a good infrared absorber, were added to the atmosphere in sufficient quantities, it would warm the surface.

Conversely, if some component of the atmosphere were to reduce the amount of sunlight reaching the surface without significantly increasing the infrared opacity, the ground temperature would decrease. For example, if all the sunlight were absorbed high in the atmosphere and none reached the ground, and if the surface could radiate energy to space without hindrance, the surface temperature would fall to that of an airless planet. If the absorption of solar energy were to take place above most of the atmosphere, the earth's radiation budget would be balanced without the greenhouse effect. (Accordingly we refer to this condition as the "anti–greenhouse effect.") Below the layer where the sunlight was absorbed the temperature of the atmosphere would not vary with altitude: at each lower level the upward infrared flux would equal the downward infrared flux and the net energy transfer would be negligible.

Particles in the atmosphere can affect the earth's radiation balance in several ways: by absorbing sunlight, by reflecting sunlight back into space and by absorbing or emitting infrared radiation. In general a cloud of fine particles—an aerosol—tends to warm the atmospheric layer it occupies, but it can either warm or cool the underlying layers and the surface, depending on whether the particles absorb infrared radiation more readily than they reflect and/or absorb visible light.

The anti–greenhouse effect of an aerosol is maximized for particles that are highly absorbing at visible wavelengths. Thus much less sunlight reaches the surface when an aerosol consists of dark particles such as soot, which strongly absorb visible light, than when an aerosol consists of bright particles such as soil dust, which mainly scatter the light. Consequently in evaluating the possible climatic effects of a nuclear war particular concern should be focused on the soot particles that are generated by fires, since soot is one of the few common particulate materials that absorb visible light much more strongly than they absorb infrared radiation.

How much an aerosol will cool the surface (by blocking sunlight) or warm the surface (by enhancing the greenhouse effect) depends on the size of the particles. If the average diameter of the particles is less than a typical infrared wavelength (about 10 micrometers), the infrared opacity of the aerosol will be less than its visible opacity. Accordingly an aerosol of very fine particles that even weakly absorb sunlight should have a visible effect greater than its infrared effect, giving rise to a significant cooling of the lower atmospheric layers and the surface. In the case of soot this is true even for somewhat larger particles.

The visible and infrared radiation effects associated with particle layers also depend on the thickness and density of the aerosol. The intensity of the sunlight reaching the ground decreases exponentially with the quantity of fine, absorbing particulate matter in the atmosphere. The infrared radiation reaching the ground, however, depends more on the air temperature than it does on the quantity of aerosol. Hence when a large amount of aerosol is present, the dominant climatic consequence tends to be strong surface cooling.

The "optical depth" of an aerosol (a measure of opacity equal to the negative natural logarithm of the attenuation of an incident light beam by absorption and scattering) serves as a convenient indicator of the aerosol's potential climatic effects. For example, a cloud with an optical depth of much less than 1

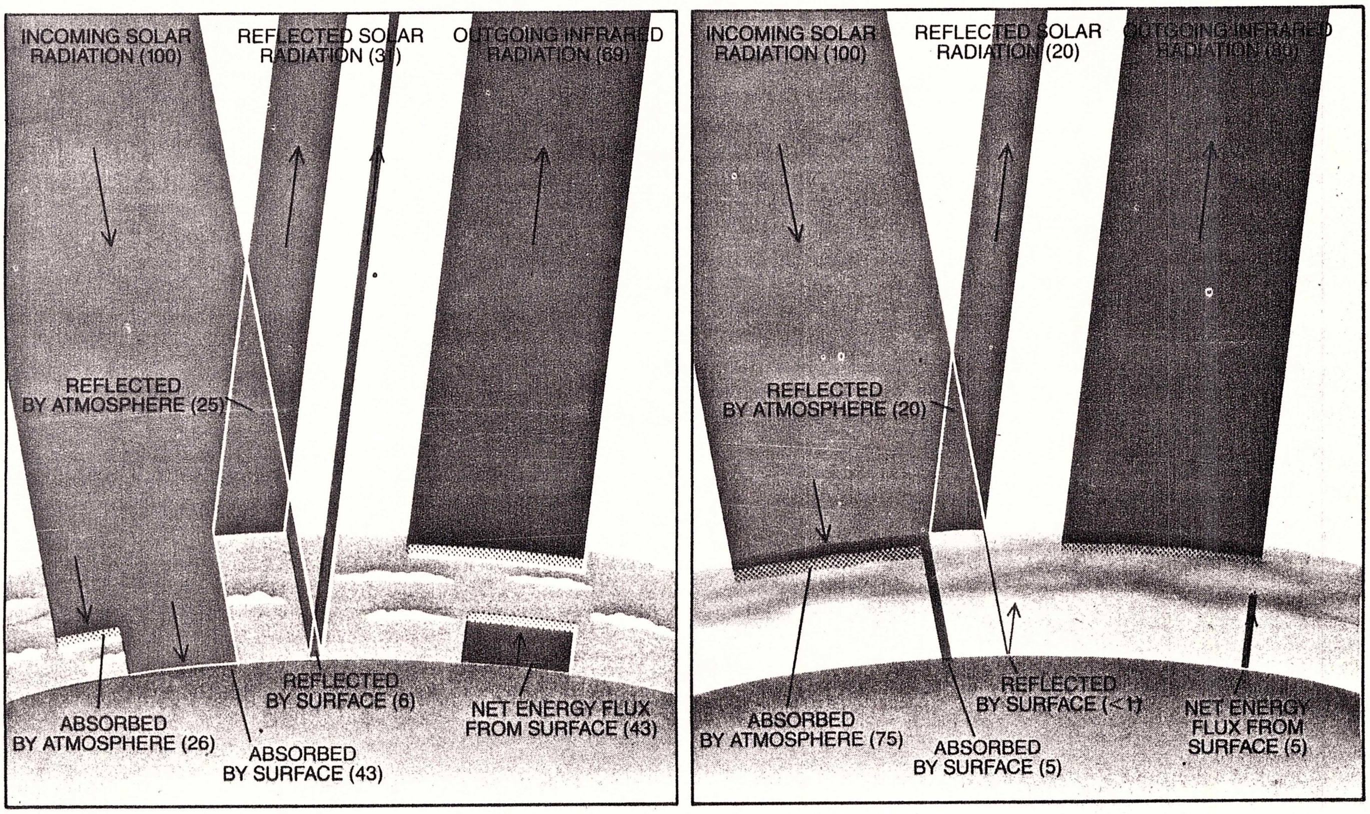
**FIRESTORM DEVELOPS in the aftermath of a one-megaton nuclear explosion over the heart of New York in the hypothetical sequence of events depicted on the opposite page. (The skyline of the city, viewed here from the west, is drawn to scale; the detonation point is assumed to be at a height of 6,500 feet directly over the Empire State Building.) In the first few seconds after the detonation the initial flash of thermal radiation from the fireball would spontaneously ignite fires in combustible materials at a considerable distance (*1*). Many of these fires would be promptly snuffed out by the passage of the spherical blast wave (*black arcs*) and the accompanying high winds, but those two effects would also start a large number of secondary fires in the process of destroying most of the city's structures (*2*). Some of the individual primary and secondary fires could then merge into major conflagrations (*3*), which in turn might coalesce into a single massive fire covering most of the city (*4*). If such a fire were intense enough and the meteorological conditions were favorable, a full-scale firestorm could ensue, driven by winds of 100 miles per hour or more in the vicinity of the central updraft (*5*). Eventually the fire would burn itself out, leaving a smoldering residue (*6*). The smoke and dust thrown up by thousands of such explosions could extend over a large region, effectively blocking the sunlight and drastically reducing the surface temperature, regardless of the season. In the authors' "base line" 5,000-megaton nuclear-war scenario little soot is injected into the stratosphere by urban firestorms; if such firestorms were common in a nuclear war, the resulting nuclear winter would be much severer than the one predicted by the computer models.**

would cause only minor perturbations, since most of the light would reach the surface, whereas a cloud with an optical depth of 1 or more would cause a major disturbance, since most of the light would be absorbed in the atmosphere and/or scattered away into space. Although volcanic particles happen to have an optimal size for enhancing visible effects over infrared effects, the magnitude of the induced surface cooling is limited by the modest optical depth of volcanic aerosols (less than about .3) and by their very weak intrinsic absorption at visible wavelengths. Nevertheless, the largest volcanic clouds may disturb the earth's radiation balance enough to cause anomalous weather. Much more significant climatic disturbances could result from the huge clouds of dust that would be thrown into the atmosphere by the impact of an asteroid or a comet with a diameter of several kilometers or more. These dust clouds could have a very large optical depth, perhaps initially as high as 1,000.

The radiative effects of an aerosol on the temperature of a planet depend not only on the aerosol's optical depth, its visible absorptivity and the average size of its particles but also on the variation of these properties with time. The longer a significant optical depth can be sustained, the closer the surface temperature and the atmospheric temperature will move toward a new state of equilibrium. Normally it takes the surface of the ocean several years to respond to changes in the global radiation balance, because of the great heat capacity of the mixed uppermost layer of the ocean, which extends to a depth of about 100 meters. In contrast, the air temperature and the continental land temperature approach new equilibrium values in only a few months. In fact, when the atmosphere is strongly cooled, convection above the surface ceases and the ground temperature falls rapidly by radiative cooling, reaching equilibrium in a few days or weeks. This happens naturally every night, although equilibrium is not reached in such a short period.

Particles are removed from the atmosphere by several processes: falling under the influence of gravity, sticking to the ground and other surfaces and scavenging by water clouds, rain and snow. The lifetime of particles against "wet" removal depends on the frequency of cloud formation and precipitation at various altitudes. In the first few kilometers of altitude in the normal atmosphere particles may in some places be washed out in a matter of days. In the upper troposphere (above five kilometers) the average lifetime of the particles increases to several weeks or more. Still higher, in the stratosphere (above 12 kilometers), water clouds rarely form and so the lifetime of small particles is typically a year or more. Stratospheric removal is primarily by gravitational settling and the large-scale convective transport of the particles. The deposition of particles on surfaces is very inefficient for average-size smoke and dust particles, requiring several months for significant depletion.

Clearly the height at which particles are injected into the atmosphere af-



**"GREENHOUSE EFFECT," the phenomenon whereby the earth's surface is warmed by the insulating properties of the atmosphere, could be negated over a large area by the cloud of smoke and dust resulting from a nuclear war. Under normal conditions (*left*) the atmosphere is quite transparent to radiation at visible wavelengths; accordingly a large fraction of the incident sunlight passes through the atmosphere and is absorbed by the surface in the form of thermal energy, or heat. Thermal radiation from the surface is emitted predominantly at longer, infrared wavelengths, which are strongly absorbed by the lower atmosphere, raising the temperature near the surface to levels well above the freezing point of water. Under normal conditions the net heat balance at the ground is the difference between a downward infrared flux of 101 units and an upward energy flux of 144 units; the latter value in turn consists of an upward infrared flux of 115 units plus an upward flux of latent and "sensible" heat totaling 29 units. The energy absorbed by the atmosphere and the surface in the form of sunlight, averaged over time, is equal to the energy emitted back into space from the surface and the atmosphere in the form of infrared radiation. A dense cloud of smoke and dust in the upper or middle atmosphere would rebalance the earth's energy budget (*right*). Most of the sunlight would then be absorbed by the cloud, and a large fraction would be reradiated directly back into space at infrared wavelengths without ever reaching the surface. Under these perturbed conditions the net heat balance at the ground would be the difference between a downward infrared flux of 65 units and an upward infrared flux of 70 units; the two fluxes would almost balance, canceling any heating effect in the atmosphere. The surface and the lower atmosphere would cool rapidly as the residual heat dissipated.**

fects their residence time. In general, the higher the initial altitude, the longer the residence time in the normal atmosphere. Massive injections of soot and dust, however, may profoundly alter both the structure of the atmosphere and the rate of particle removal.

In our analysis of the climatic effects of nuclear war we have adopted a number of specific scenarios, based on what is publicly known about the effects of individual nuclear explosions, the size and deployment of the world's present nuclear arsenals and the nuclear-war-fighting plans of the U.S. and the U.S.S.R. Among the several dozen cases we have analyzed are a 100-megaton "countervalue" attack directed strictly against cities, a 3,000-megaton "counterforce" attack directed strictly against missile silos and a 10,000-megaton "full-scale exchange" directed against an assortment of targets on both sides. Our "base line" case is a 5,000-megaton nuclear exchange, with about 20 percent of the total explosive yield detonated over urban, suburban and industrial areas. All the postulated attack scenarios are well within the present capabilities of the two superpowers.

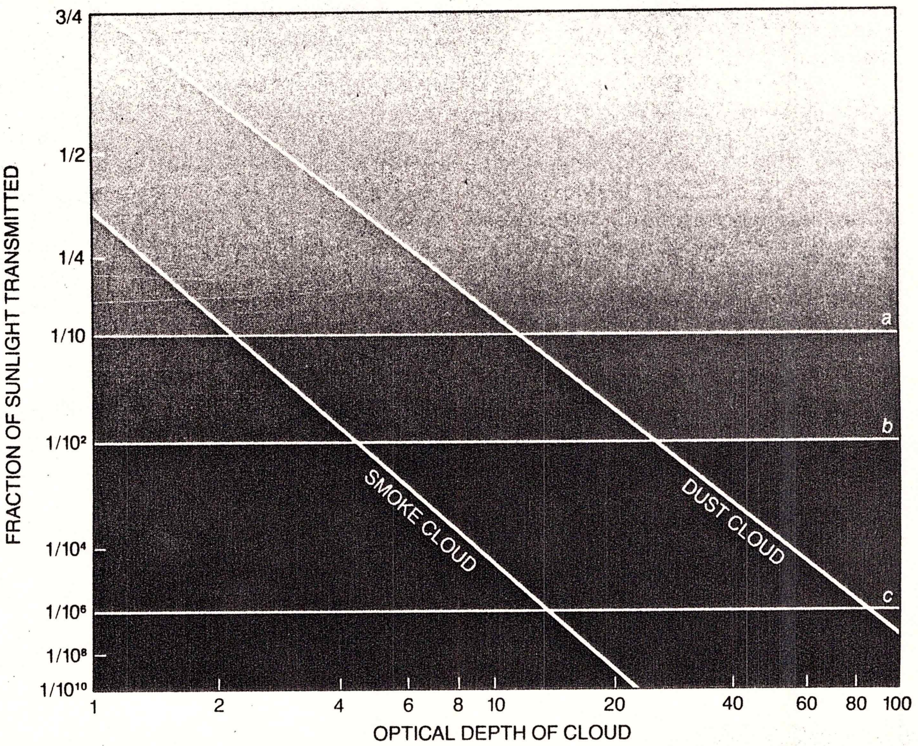
A nuclear explosion can readily ignite fires in either an urban or a rural setting. The flash of thermal radiation from the nuclear explosion, which has a spectrum similar to that of sunlight, accounts for about a third of the total energy yield of the explosion. The flash is so intense that a variety of combustible materials are ignited spontaneously at ranges of 10 kilometers or more from a one-megaton air burst detonated at a nominal altitude of a kilometer. The blast wave from the explosion would extinguish many of the initial fires, but it would also start numerous secondary fires by disrupting open flames, rupturing gas lines and fuel storage tanks and causing electrical and mechanical sparks. The destruction resulting from the blast wave would also hamper effective fire fighting and so promote the spread of both the primary and the secondary fires. Based on the known incendiary effects of the nuclear explosions over Hiroshima and Nagasaki in 1945 it can be projected that the fires likely to be caused by just one of the far more powerful strategic nuclear weapons available today would extend over an area of from tens to hundreds of square kilometers.

Nuclear explosions over forests and grasslands could also ignite large fires, but this situation is more difficult to evaluate. Among the factors that affect fires in wilderness areas are the humidity, the moisture content of the fuel, the amount of the fuel and the velocity of the wind. Roughly a third of the land area in the North Temperate Zone is covered by forest, and an equal area is covered by brush and grassland. Violent wildfires have been known to spread over tens of thousands of square kilometers from a few ignition points; in the absence of a nuclear war such fires occur about once every decade. Although most wildfires generated by nuclear explosions would probably be confined to the immediate area exposed to the intense thermal flash, it is possible that much larger ones would be started by multiple explosions over scattered military targets such as missile silos.

The total amount of smoke likely to be generated by a nuclear war depends on, among other things, the total yield of the nuclear weapons exploded over each type of target, the efficiency of the explosions in igniting fires, the average area ignited per megaton of yield, the average amount of combustible material in the irradiated region, the fraction of the combustible material consumed by the fires, the ratio of the amount of smoke produced to the amount of fuel burned and the fraction of the smoke that is eventually entrained into the global atmospheric circulation after local rainfall has removed its share. By assigning the most likely values to these parameters for a nuclear war involving less than 40 percent of the strategic arsenals of the two superpowers we were able to calculate that the total smoke emission from a full-scale nuclear exchange could easily exceed 100 million metric tons. In many respects this is a conservative estimate. Crutzen and his co-workers Ian Galbally of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia and Christoph Brühl of the Max Planck Institute at Mainz have recently estimated that the total smoke emission from a full-scale nuclear war would be closer to 300 million tons.

One hundred million tons of smoke, if it were distributed as a uniform cloud over the entire globe, could reduce the intensity of sunlight reaching the ground by as much as 95 percent. The initial clouds would not cover the entire globe, however, and so large areas of the Northern Hemisphere, particularly in the target zones, would be even darker; at noon the light level in these areas could be as low as that of a moonlit night. Daytime darkness in this range, if it persisted for weeks or months, would trigger a climatic catastrophe. Indeed, significant disturbances might be caused by much smaller amounts of smoke.

Wildfires normally inject smoke into the lower atmosphere to an altitude of five or six kilometers. In contrast, large urban fires have been known to inject smoke into the upper troposphere, probably as high as 12 kilometers. The unprecedented scale of the fires likely to be ignited by large nuclear explosions and the complex convective activity generated by multiple explosions might cause some of the smoke to rise even higher. Studies of the dynamics of very large fires suggest that individual smoke



**TRANSMISSION OF SUNLIGHT** through smoke clouds and dust clouds is represented in this graph as a function of each cloud's optical depth, a measure of opacity equal to the negative natural logarithm of the attenuation of an incident light beam. At a given optical depth a smoke cloud evidently absorbs much more sunlight than a dust cloud. Three typical levels of transmitted light are given for comparison: they correspond to a very cloudy day (*a*), a light level at which photosynthesis is barely possible (*b*) and a clear night with a full moon (*c*).

plumes might reach as high as 20 kilometers, well into the stratosphere.

During the World War II bombing of Hamburg the center of the city was gutted by an intense firestorm, with heat-generated winds of hurricane force sweeping inward from all directions at ground level. Rapid heat release over a large area can create fire vortexes, heat tornadoes and cyclones with towering convective columns. The sheer intensity of such fires might act to reduce the smoke emission considerably through two processes: the oxidation of carbonaceous smoke particles at the extremely high temperatures generated in the fire zone and the washout of smoke particles by precipitation formed in the convective column. Both effects were taken into account in our estimates of the total smoke emission from a nuclear war.

The climatic impact of smoke depends on its optical properties, which in turn are sensitive to the size, shape and composition of the smoke particles. The most effective light-screening smoke consists of particles with a radius of about .1 micrometer and a very sooty composition rich in graphite. The least effective smoke in attenuating sunlight consists of particles larger than .5 micrometer with a predominantly oily composition. The smoke from a forest fire is typically composed of extremely fine oily particles, whereas the smoke from an urban fire consists of larger agglomerations of sooty particles. Smoke from fierce fires usually contains large particles of ash, char, dust and other debris, which is swept up by the heat-generated winds. The largest of these particles fall out of the smoke clouds just downwind of the fire. Although very intense fires produce less smoke, they lift more fine dust and may burn metals such as aluminum and chromium, which efficiently generate fine aerosols.

The release of toxic compounds in urban fires has not been adequately studied. It is well known that many people who have died in accidental fires have been poisoned by toxic gases. In addition to carbon monoxide, which is produced copiously in many fires, hydrogen cyanide and hydrogen chloride are generated when the synthetic compounds in modern building materials and furnishings burn. If large stores of organic chemicals are released and burned in a nuclear conflict, additional airborne toxins would be generated. The possibility that vast areas could be contaminated by such pyrotoxins, adsorbed on the surface of smoke, ash and dust particles and carried great distances by winds, needs further investigation.

Nuclear explosions at or near ground level throw up huge amounts of dust. The principal dust-forming mechanisms include the ejection and disaggregation of soil particles from the crater formed by the explosion; the vaporization and subsequent renucleation of soil and rock, and the lifting of surface dust and smoke. A one-megaton explosion on land can excavate a crater hundreds of meters in diameter, eject several million tons of debris, lift between 100,000 and 600,000 tons of soil to a high altitude and inject between 10,000 and 30,000 tons of submicrometer dust particles into the stratosphere. The height at which the dust is injected depends on the yield of the explosion: the dust clouds produced by explosions with a yield of less than about 100 kilotons will generally not penetrate into the stratosphere, whereas those from explosions with a yield of more than about a megaton will stabilize mainly within the stratosphere. Explosions above the ground can also raise large quantities of dust, which is vacuumed off the surface by the rising fireball. The combined effects of multiple explosions could enhance the total amount of dust raised to high altitudes.

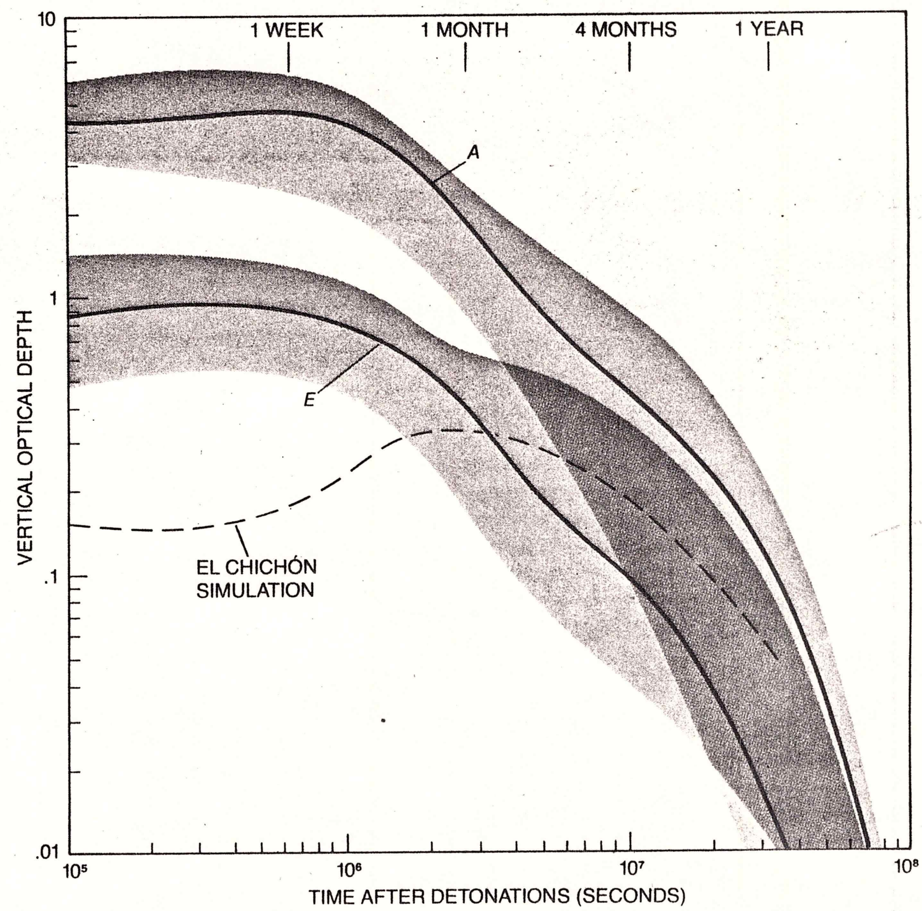
The quantity of dust produced in a nuclear war would depend sensitively on the way the weapons were used. Ground bursts would be directed at hard targets, such as missile silos and underground command posts. Soft targets could be attacked by air bursts as well as ground bursts. There are more than 1,000 missile silos in the continental U.S. alone, and at least two Russian warheads are probably committed to each of them. Some 1,400 missile silos in the U.S.S.R. are similarly targeted by U.S. warheads. Air bases and secondary airfields, submarine pens and command and control facilities are among the many other strategic targets to which ground bursts might be assigned. In short, it seems quite possible that at least 4,000 megatons of high-yield weapons might be detonated at or near ground level even in a war in which cities were not targeted, and that roughly 120 million tons of submicrometer soil particles could be injected into the stratosphere in the North Temperate Zone. This is many times greater than all the submicrometer dust lifted into the stratosphere by the eruption of the volcano El Chichón in Mexico in 1982 and is comparable to the global submicrometer dust injections of much larger volcanic eruptions such as that of Tambora in 1815 and Krakatau in 1883.

| | SCENARIO | TOTAL YIELD (MEGATONS) | SURFACE BURSTS (PERCENTAGE OF YIELD) | URBAN OR INDUSTRIAL TARGETS (PERCENTAGE OF YIELD) | YIELD OF WARHEADS (MEGATONS) | TOTAL NUMBER OF EXPLOSIONS | MASS OF SUB-MICROMETER SMOKE (MILLIONS OF METRIC TONS) | MASS OF SUB-MICROMETER DUST (MILLIONS OF METRIC TONS) | OPTICAL DEPTH OF SMOKE | OPTICAL DEPTH OF DUST |
|---|---|---|---|---|---|---|---|---|---|---|
| *A* | BASE-LINE EXCHANGE | 5,000 | 57 | 20 | .1–10 | 10,400 | 225 | 65 | 4.5 | 1 |
| *B* | LOW-YIELD AIRBURSTS | 5,000 | 10 | 33 | .1–1 | 22,500 | 300 | 15 | 6 | .2 |
| *C* | FULL-SCALE EXCHANGE | 10,000 | 63 | 15 | .1–10 | 16,160 | 300 | 130 | 6 | 2 |
| *D* | MEDIUM-SCALE EXCHANGE | 3,000 | 50 | 25 | .3–5 | 5,433 | 175 | 40 | 3.5 | .6 |
| *E* | LIMITED EXCHANGE | 1,000 | 50 | 25 | .2–1 | 2,250 | 50 | 10 | 1 | .1 |
| *F* | GENERAL COUNTERFORCE ATTACK | 3,000 | 70 | 0 | 1–10 | 2,150 | 0 | 55 | 0 | .8 |
| *G* | HARD-TARGET COUNTERFORCE ATTACK | 5,000 | 100 | 0 | 5–10 | 700 | 0 | 650 | 0 | 10 |
| *H* | CITY ATTACK | 100 | 0 | 100 | .1 | 1,000 | 150 | 0 | 3 | 0 |
| *I* | FUTURE WAR | 25,000 | 72 | 10 | .1–10 | 28,300 | 400 | 325 | 8 | 5 |

**NUCLEAR-WAR SCENARIOS outlined in this table were drawn from a much longer list of possibilities considered in detail by the authors in their original study. The last four columns at the right give the outcome of each scenario in terms of the resulting clouds of smoke and dust. All the scenarios shown here except the last one are thought to be well within the present capabilities of the two superpowers.**

Analogies between the atmospheric effects of a major volcanic explosion and a nuclear war are often made for convenience. Nevertheless, there is no straightforward way to scale the effects of a volcanic explosion against those of a series of nuclear detonations. The aerosol particles produced by volcanoes are fundamentally different in composition, size and shape from those produced by nuclear explosions. We have therefore based our calculations on the properties of dust measured directly in nuclear-explosion clouds.

The only proper comparison between a volcanic eruption and a nuclear explosion is the optical depth of the long-term aerosols that are produced. In fact, we utilized data on global "dust veils" generated by volcanic explosions to test and calibrate our climate models. In so doing we have been able to account quantitatively for the hemispheric surface-cooling effect observed after major volcanic eruptions. The present nuclear-dust calculations are entirely consistent with observations of volcanic phenomena. For example, it is now clear that violent eruptions can lead to a significant climatic cooling for a year or more. Even so, in recorded history volcanoes have had only a rather modest climatic role. The fact that volcanoes are localized sources of dust limits their geographic influence; moreover, volcanoes inject comparatively little fine dust (and no soot) into the stratosphere. Nuclear explosions, on the other hand, are a powerful and efficient means of injecting large quantities of fine soot and dust into the atmosphere over large regions.



**VARIATION IN OPACITY OVER TIME** of the clouds of smoke and dust resulting from a number of nuclear-war scenarios is traced here in terms of the clouds' vertical optical depth averaged over the Northern Hemisphere. The optical depths were calculated for visible light at a wavelength of 550 nanometers. The results tend to fall into two bands. The upper band includes those scenarios that gave results close to the authors' 5,000-megaton base-line case, indicated by the solid-color curve; the total explosive yields of the scenarios in this band range from 100 to 10,000 megatons. The lower band includes those scenarios that gave less drastic results; the scenarios in this band range from the 1,000-megaton limited exchange indicated by the black curve to a 3,000-megaton counterforce attack aimed at military targets only. Significant climatic disruptions are expected whenever the average optical depth over a hemisphere is greater than about 1. The average optical depth over the Northern Hemisphere of the cloud of dust raised by the eruption of the volcano El Chichón in 1982 is given for comparison.

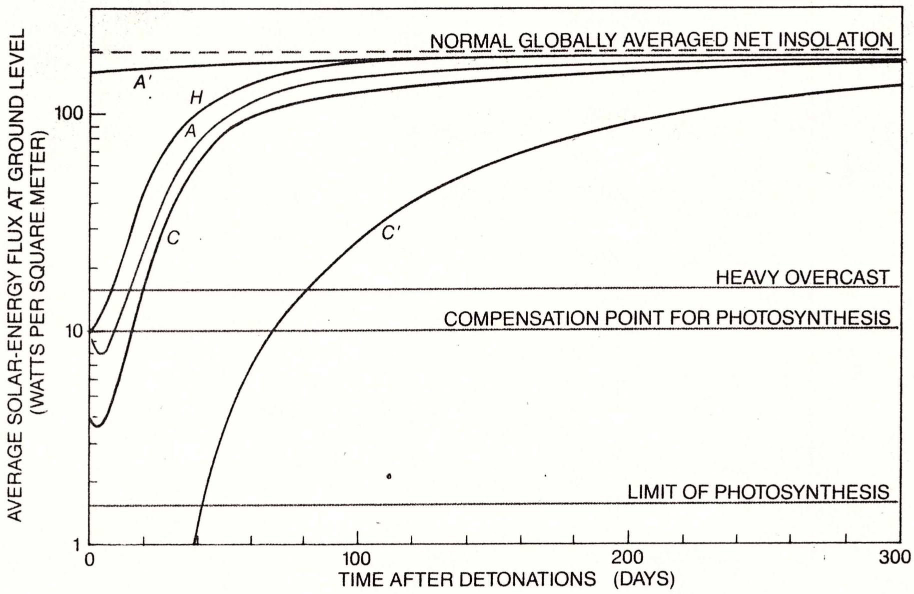
The atoms produced in the fission reactions of a nuclear explosion are often in unstable isotopic states. Radioactive decay from these states releases alpha, beta and gamma radiation. In most nuclear weapons at least half of the energy yield is generated by fission and the rest by fusion. About 300 distinct radioactive isotopes are produced. Most of them condense onto aerosols and dust formed in (or sucked into) the fireball. Accordingly the dust and the radioactivity generated by nuclear explosions are intimately related.

Of particular interest here are the prompt and the intermediate radioactive fallout. The former is associated with short-lived radioactive isotopes that condense onto large soil particles, which in turn fall to the ground within hours after an explosion. Intermediate fallout is associated with longer-lived radioactive isotopes carried by smaller particles that drift in the wind and are removed by settling and precipitation in the interval from days to months. Prompt fallout is generated by ground bursts, and intermediate fallout is generated by ground bursts and air bursts in the yield range from 10 to 500 kilotons, which deposit their radioactivity in the middle and upper troposphere.

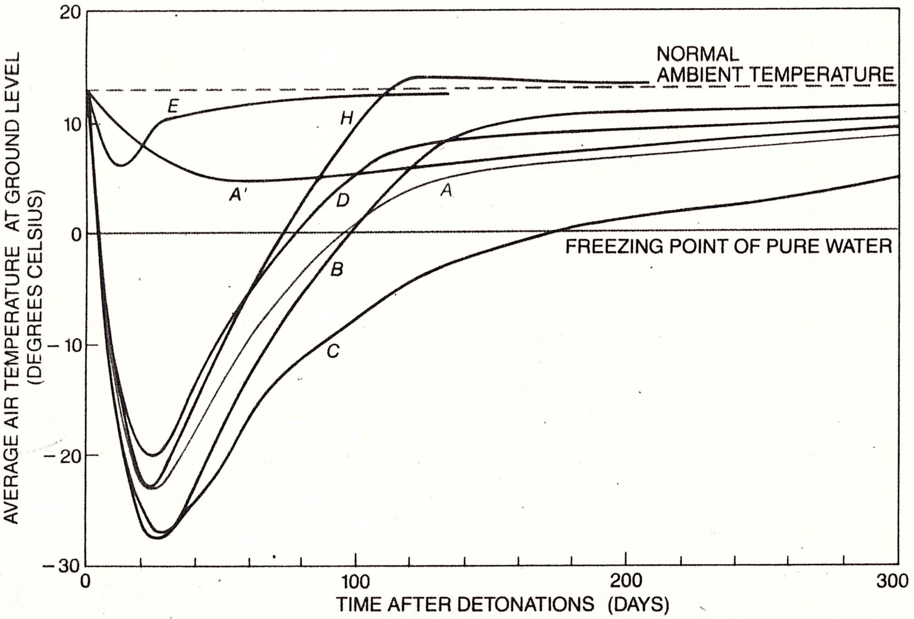
The danger from radioactive fallout is measured in terms of the total dose in rads (a unit of radiation exposure equivalent to 100 ergs of ionizing energy deposited in one gram of tissue), the dose rate in rads per hour and the type of radiation. The most deadly effects are caused by the intense, penetrating gamma radiation from prompt fallout. The widespread intermediate fallout delivers a less potent long-term gamma-ray dose. A whole-body gamma-ray exposure of 450 rads, received over several days, is lethal to half of the healthy adults exposed. Chronic doses of 100 rads or more from intermediate fallout could suppress the immune system even of healthy people and would cause long-term increments in the incidence of cancer, genetic defects and other diseases.

Our most recent studies of the effects of radioactive fallout in our base-line case indicate that the prompt fallout could contaminate millions of square kilometers of land with lethal radioactivity. The intermediate fallout would blanket at least the North Temperate Zone, producing average long-term, whole-body gamma-ray exposures of about 50 rads in unprotected populations. Internal exposures of specific organs to biologically active radioactive isotopes such as strontium 90 and iodine 131, which enter the food chain, could double or triple the total doses. According to Joseph B. Knox of the Lawrence Livermore National Laboratory, if nuclear power plants were targeted directly, the average long-term gamma-ray dose could be increased to several hundred rads or more.

The computer models we have employed to define the potential magnitude of the long-term global aftereffects of nuclear war are one-dimensional: they treat only the vertical structure of the atmosphere. Obviously the atmosphere is a complex three-dimensional system



**VARIATION IN THE AMOUNT OF SUNLIGHT** reaching the ground through a widely dispersed cloud of smoke and dust created by a nuclear war is shown for several of the nuclear-war scenarios considered by the authors. Each curve gives the average solar-energy flux at the ground in the Northern Hemisphere for a given scenario. The fluxes correspond to horizontally averaged smoke clouds and do not take into account possible patchiness in the clouds. The color curve corresponds to the 5,000-megaton base-line case (*curve A*). Curve $A'$ is a variant of the base-line case that takes into account only the effects of dust. Curve $C'$ is a variant of the 10,000-megaton full-scale exchange that assigns more extreme values to the smoke-emission parameters. Also indicated are the energy level at which photosynthesis cannot keep pace with the respiration of a typical plant (a level known as the compensation point) and the energy level at which photosynthesis ceases. These two thresholds vary considerably from plant to plant.



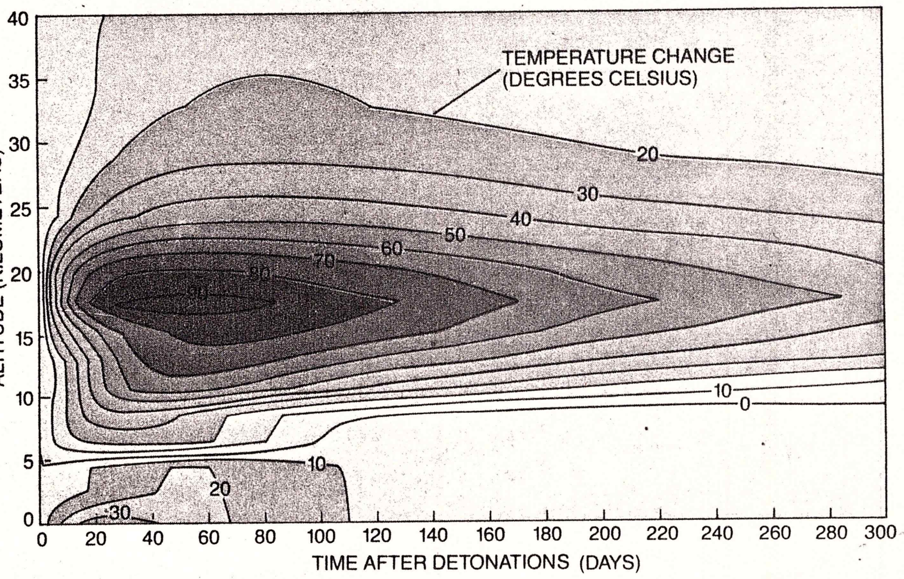
**VARIATION IN TEMPERATURE** at ground level in the Northern Hemisphere with time after a nuclear war is shown for several scenarios. Again the color curve corresponds to the authors' 5,000-megaton base-line case. In general smoke in the troposphere (below 12 kilometers) would have a substantial short-term cooling effect, whereas dust in the stratosphere (above 12 kilometers) would result in a less pronounced but longer cooling trend. The calculated average temperature decrease in each case is probably the largest that would be registered, and then only in the interior regions of the continents. The temperature decrease over the ocean would be only a few degrees Celsius or less. Hence the mixing of continental and marine air masses would lead to a less drastic temperature decrease over land, particularly along coastlines. The same phenomenon, however, would also lead to prolonged severe coastal storms. The temperature changes plotted in this graph are seasonally averaged. If the war were in the summer, the temperature decrease would be larger than that indicated in each case; if the war were in the winter, the temperature decrease would be smaller. A decline in temperature of only a few degrees may have significant adverse effects on agriculture. In a wide range of cases the temperature drops to −20 degrees C. or lower and does not return to the freezing point for months.

whose intricate interactions determine its response to perturbations. At present, however, there are no three-dimensional models with the appropriate features to treat the nuclear-winter problem with high precision, although several such models are under development. The existing models of the climate and the general circulation of the atmosphere incorporate a number of empirical approaches to physical processes that are not well understood. In the nuclear-winter scenario the climate is so seriously perturbed that such treatments are of dubious applicability.

Our approach has therefore been to estimate the first-order effects through detailed microphysical, chemical and optical calculations in a one-dimensional format. Even this simplified approach had not been attempted before our work, and it was not clear then that more sophisticated three-dimensional work was justified. Based on the predicted first-order one-dimensional effects, the principal three-dimensional meteorological interactions that would have to be treated in more refined studies were deduced. The three-dimensional results generally confirm our one-dimensional results.

Three basic models were used in our study: a nuclear-scenario model, a particle-microphysics model and a radiative-convective climate model. The nuclear-scenario model determines the quantities of smoke, dust, radioactivity and pyrotoxins generated by a specific nuclear exchange, relying on (among other things) the smoke and dust estimates cited above. The microphysics model simulates the evolution of the quantity and the size of the smoke and dust particles and the deposition of radioactivity by accounting for the physical interactions and vertical transport of particles at all altitudes. The radiative-convective model calculates the optical and infrared properties of the evolving particles, the visible and infrared energy fluxes and air temperatures as a function of time and altitude. Because the predicted air temperatures are sensitive to surface heat capacities, separate calculations were done for land and ocean environments to define possible temperature differences.

One-dimensional models cannot accurately forecast the short-term or local effects of a nuclear war. The applicability of the predictions based on such models depends on the rate and extent of the dispersion of the smoke plumes and dust clouds. Soon after a nuclear exchange thousands of individual smoke and dust clouds would be distributed throughout the North Temperate Zone at altitudes of up to 20 kilometers. The action of horizontal turbulent diffusion, vertical wind shear and continuing smoke emission would almost certainly spread the



**VARIATION IN TEMPERATURE WITH ALTITUDE** over the northern continents is plotted in this contour diagram for the first year after the 5,000-megaton base-line nuclear war. The contours give the average change in temperature at intervals of 10 degrees C., based on the authors' one-dimensional radiative-convective model. The gray area indicates parts of the atmosphere that are cooled below their normal temperature; the color area indicates parts that are heated above their normal temperature. The strong heating effect in the upper troposphere and lower stratosphere is attributable mainly to the absorption of sunlight by smoke and dust.

clouds of nuclear debris over the entire zone and fill in gaps in the clouds within a week. Local effects in this period could vary considerably from the average effects simulated with our one-dimensional models.

Since large uncertainties are inherent in any assessment of the effects of nuclear warfare, a variety of simulations were made to investigate the sensitivity of various outcomes to changes in scenarios and in key physical parameters. Although all these results cannot be discussed in an article of this length, some selected findings are summarized in the illustrations accompanying this article.

In general our results suggest that the optical depth of the cloud of smoke and dust resulting from a massive nuclear exchange would at the very least be comparable to or larger than that of the cloud resulting from a major volcanic eruption, and that the most probable optical depth would be an order of magnitude larger. The likeliest outcome of a nuclear war would therefore be a climatic catastrophe.

The ultimate impact of smoke and dust on climate depends on the fraction of sunlight they screen from the surface. This suggests that a saturation effect will occur. For example, a smoke cloud with an optical depth of 3 can prevent 95 percent or more of the sunlight from reaching the ground. Greater optical depths cause only negligible further decreases in the average surface sunlight. Thus an average optical depth of about 3 is roughly the saturation level for smoke-induced climatic effects. The saturation level for dust occurs at an optical depth of about 20, and its onset is much more gradual with increasing optical depth than the saturation level for smoke. It is doubtful whether enough dust could be raised in a nuclear war to create optical saturation on a global scale.

How a smoke cloud extinguishes light also differs from how a dust cloud does so. A sooty pall of smoke absorbs most of the incident light and scatters only a small fraction back into space or down toward the surface. The absorption rapidly heats the smoke clouds, inducing powerful air motions and winds. Dust clouds, on the other hand, primarily scatter the incident sunlight and absorb only a small fraction. To block light effectively clouds that are purely light-scattering must be very thick, because much of the light is scattered forward toward the earth's surface; for example, ordinary water clouds typically have an optical depth of 10 or more.

We find that for many scenarios a substantial reduction in sunlight may persist for weeks or months after the war. In the first week or two the clouds would also be patchy; hence our calculations probably underestimate the average light intensity at these early stages. Nevertheless, within the target zones it would be too dark to see, even at noon.

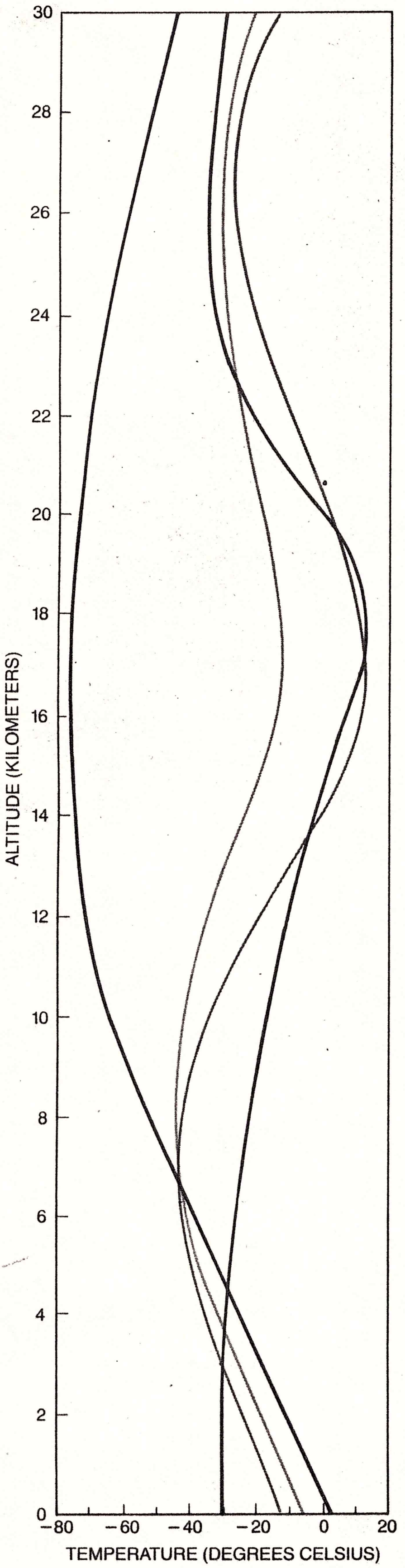
The large amount of smoke generated by a nuclear exchange could lead to dramatic decreases in continental temperatures for a substantial period. In many of the scenarios represented in the illustrations accompanying this article land temperatures remain below freezing for months. Average temperature decreases of only a few degrees Celsius in spring or early summer could destroy crops throughout the North Temperate Zone. Temperature drops of some 40 degrees C. (to an absolute temperature of about −25 degrees C.) are predicted for the base-line case, and still severer cooling effects are possible with the current nuclear arsenals and with those projected for the near future.

The predicted changes in air temperature as a function of height and time for our 5,000-megaton base-line scenario reveal several important features. First, the upper atmosphere is heated by between 30 and 80 degrees C. as the sunlight, which normally warms the ground, is absorbed in the highest smoke layers. At the same time the ground cools in darkness. The hot clouds, like hot-air balloons, would not remain stationary but would rise and expand.

A month after a massive nuclear exchange the entire troposphere over land could be thermally brought to a standstill. Even after three months only the lowest few kilometers would receive enough solar energy to drive weak convection. In effect the stratosphere would descend to the surface, creating an alien atmosphere. In some places warm currents of ocean air would still sweep into the continents at ground level, but this heat source would be able to drive convection only within the lowest few kilometers of the atmosphere. The intense temperature inversion would effectively damp deep convective activity. Elsewhere cold air flowing off the continents might warm over the oceans, rise and recirculate over the continents and finally subside over the land.

One possible consequence of the temperature inversion caused by such a smoke cloud would be an increase in the atmospheric residence time of the smoke and dust. This outcome represents a positive feedback effect, not taken into account in any calculations so far, that would increase both the severity and the duration of the nuclear winter. The temperature inversion reduces the convective penetration of moist air from below, inhibiting the condensation of water in the sooty air and hence greatly limiting precipitation at altitudes higher than a few kilometers. The longer soot and dust remain in the atmosphere, the farther they spread horizontally and the more widespread their climatic impact is. Under these conditions the particles are removed mainly by continuing coagulation and fallout and by transport in global-scale wind systems and turbulence to low altitudes where precipitation scavenging still takes place.

Our calculated temperature changes over extended land masses do not account for the initial patchiness in the clouds or the later dilution of cold continental air by warm marine air. Michael C. MacCracken of Livermore has investigated the combined effects of patchi-



**TEMPERATURE PROFILES of the atmosphere before and after a 5,000-megaton nuclear war are compared. The black curve is the normal temperature profile. The other curves show the profile one month after the war (*dark color*), three months after (*medium color*) and six months after (*light color*).**

ness in clouds and the transfer of heat from the ocean, working with a general-circulation model to trace large blobs of smoke; he has also worked with a two-dimensional climate model to calculate land temperatures corresponding to the smoke emission in our 5,000-megaton base-line scenario. He finds average temperature decreases on land that are roughly half our continental-interior temperature drops. Even more sophisticated three-dimensional general-circulation-model calculations for conditions similar to our base-line scenario confirm that temperature drops of between 20 and 40 degrees C. are possible over vast continental areas.

The results of our computations indicate that the motions induced in soot clouds by the absorption of sunlight might cause the soot cloud to rise and spread out horizontally. This phenomenon could accelerate both the early dispersal and the global spreading of smoke plumes, a process that is otherwise dominated by wind shear and turbulence. Recently a group at the National Aeronautics and Space Administration's Ames Research Center, consisting of Robert M. Haberle and two of us (Ackerman and Toon), applied an advanced two-dimensional global-circulation model to compute the motion of heated soot clouds in the earth's troposphere. The Ames group considered a uniform soot cloud between 30 and 60 degrees north latitude, encircling the earth at these latitudes and extending from the ground to an altitude of eight kilometers. This smoke simulation shows massive fragments of the cloud rising high into the stratosphere and moving briskly toward the Equator and the Southern Hemisphere.

Although these calculations are preliminary, they support a major hypothesis of our initial study: that self-propelled smoke and dust clouds from the Northern Hemisphere could be rapidly transported to the Southern Hemisphere, causing large climatic anomalies there as well. Such accelerated dispersal could have the most severe consequences in the Tropics of both hemispheres, where the indigenous organisms are extremely sensitive to dark and cold. A nuclear winter extending to the Tropics would represent an ecological disaster unprecedented in history.

Our speculations about major meteorological disturbances and interhemispheric transport following a nuclear conflict have received further support from sophisticated calculations with three-dimensional models of global circulation. These models are not yet designed to move smoke and dust as tracer elements or to make the required detailed radiative-transport calculations. Nevertheless, they are able to define the initial three-dimensional perturbations in winds and temperatures caused by massive smoke injections. Two research groups have made these advanced climate studies: Curt Covey, Stephen H. Schneider and Starley L. Thompson of the National Center for Atmospheric Research (NCAR) in Boulder, Colo., and Vladimir V. Alexandrov and Georgi L. Stenchikov of the Computing Center of the Academy of Sciences of the U.S.S.R.

The predictions made by both groups of the normal and perturbed meridional, or north-south, circulation of the atmosphere several weeks after a nuclear exchange in the Northern Hemisphere in the spring or summer lead to the same conclusion: the normally bifurcated "Hadley cell" circulation in the Tropics would be transformed into a single intense cell with strong winds in the upper troposphere flowing directly from the Northern Hemisphere to the Southern Hemisphere. This would represent a profound change in the global wind system.

The average meridional circulation is the residual motion of large-scale planetary-wave oscillations. The global-circulation models predict anomalies in the planetary-wave motions, and here too the results are surprising. The NCAR group finds that continent-size bodies of heated air could penetrate deep into the Southern Hemisphere in a matter of days. Essentially all the habitable land masses of the earth could be subject to rapid blackout by soot. The global-circulation models also forecast subfreezing temperatures over most of the northern continental regions. What is startling is that local freezing could occur within two or three days; the NCAR group refers to it as a "quick freeze." Under such circumstances practically no area of the globe, north or south, would be safe from nuclear winter.

Consideration of the possible weather activity near coastlines during the nuclear winter suggests that even if the incident sunlight were reduced significantly, the oceans would continue to feed heat and moisture into the marine boundary layer near coastlines. In some regions cold offshore winds would interact with the marine environment to produce intense storms and heavy precipitation. In other regions, as prevailing winds swept ocean air onto cold continents, thick stratus clouds and continuous precipitation could ensue. It is not known how far this severe weather might extend inland from the coastlines, but a 100-kilometer margin would probably include most of the activity.

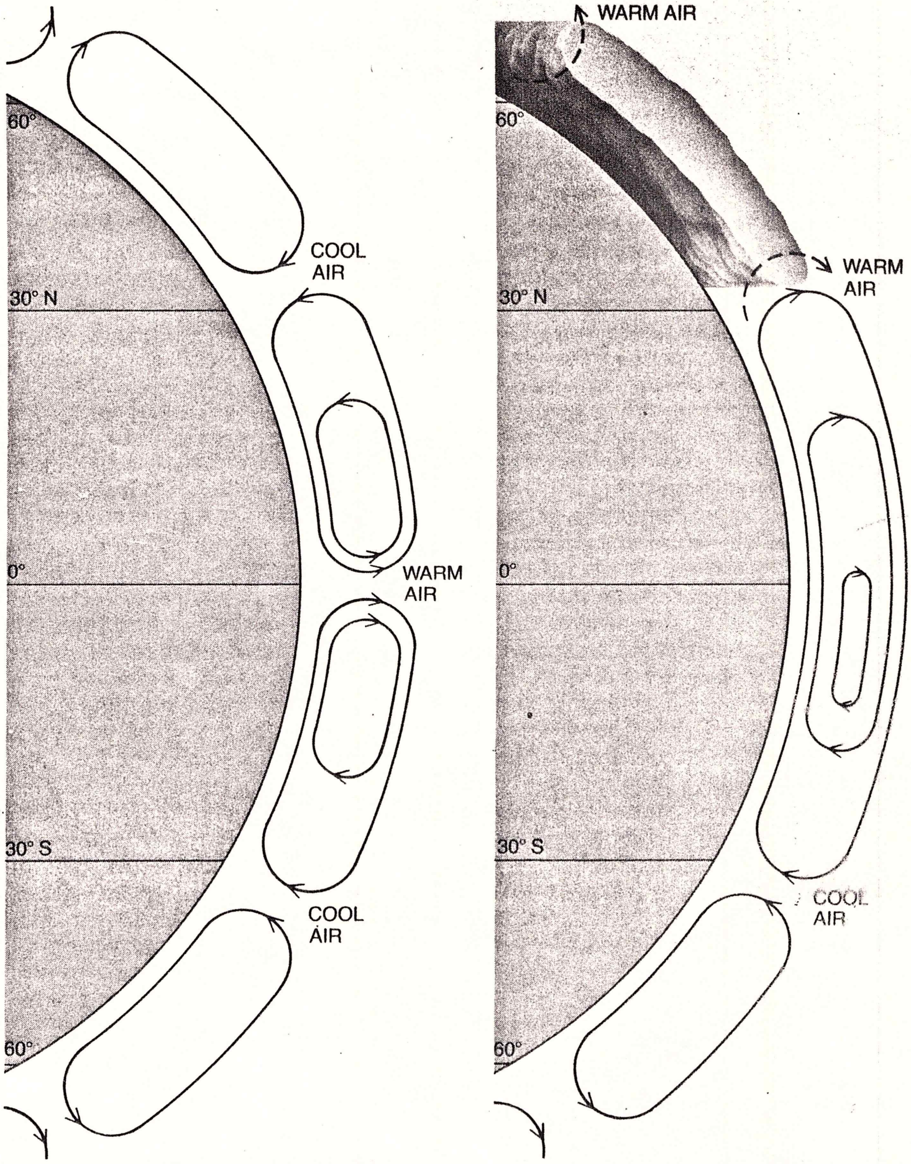
There are many additional questions about nuclear winter that remain to be answered. With rapid surface cooling widespread fogs would develop, and they might affect the radiation balance at the surface. The presence of millions of tons of nuclear debris in the atmosphere could modify the properties of cloud droplets and so the removal rate of the debris. The nuclear clouds and modified natural clouds would also affect the overall infrared-radiation balance of the atmosphere, but the implications for surface temperatures remain uncertain. Daily variations, which have not yet been treated in the climate models applied to the nuclear-war problem, could also influence the dynamics and removal of the nuclear debris. Water injected by nuclear explosions and fires might affect atmospheric chemical and radiative processes. All these effects are important second-order refinements of the basic climatic theory of the nuclear winter. On the basis of the existing scientific evidence, however, none of these effects appears to be capable of significantly altering the major climatic impacts now predicted for a nuclear war.

There is also a lack of understanding of the interactions of the atmosphere with the oceans, which may have a major influence on short-term climatic changes. Through what was perhaps a series of coincidences, the eruption of El Chichón in the spring of 1982 was followed by an unusually intense El Niño warming of the South Pacific in the winter of 1982 and spring of 1983, associated with an unexpected calming of the southerly trade winds. These events were followed by unusual weather in North America and Europe in the winter of 1982 and throughout 1983. Most of North America suffered record-breaking cold that winter, and Europe enjoyed a balmy spring in December. Although proof that these events were related is lacking, the evidence suggests a potentially significant coupling of ocean currents, winds and weather on a comparatively short time scale; such a relation has yet to be defined rigorously.

Our study also considered a number of secondary climatic effects of nuclear war. Changes in the albedo, or reflectivity, of the earth's surface can be caused by widespread fires, by the deposition of soot on snow and ice and by regional modifications of vegetation. Short-term changes in albedo were evaluated and found to be unimportant compared with the screening of sunlight. If significant semipermanent albedo changes were to occur, long-term climatic shifts could ensue. On the other hand, the vast oceanic heat source would act to force the climate toward contemporary norms following any major disturbance. Accordingly we have tentatively concluded that a nuclear war is not likely to be followed by an ice age.

We have also analyzed the climatic effects caused by changes in the gaseous composition of the atmosphere. The maximum hemispheric temperature perturbation associated with the production of oxides of nitrogen and the accompanying depletion of ozone is a cooling of no more than a few degrees C. The concentrations of greenhouse-effect gases would also be modified by a nuclear war; such gases might produce a surface warming of several degrees after the smoke and dust had cleared. These mutually offsetting temperature perturbations are uncertain, however, because the chemical and physical changes in the atmosphere caused by a nuclear war would be coupled through processes that are not adequately treated in existing models. Further analysis is clearly needed on this point.

Of course, the actual consequences of a nuclear war can never be precisely foreseen. Synergistic interactions among individual physical stresses might compound the problem of survival for many organisms. The long-term destruction of the environment and the disruption of the global ecosystem might in the end prove even more devastating for the human species than the awesome short-term destructive effects of nuclear explosions and their radioactive fallout. The strategic policies of both superpowers and their respective military alliances should be reassessed in this new light.



**GLOBAL CIRCULATION PATTERN** of the atmosphere could be disrupted by a major nuclear war in the Northern Hemisphere. In the spring and summer (in the Northern Hemisphere) the average global circulation in the meridional, or north-south, direction is dominated by the large convective feature called a Hadley cell, in which the air rises over the hot, humid Tropics, splits into two streams and descends over subtropical and middle latitudes in both hemispheres, establishing secondary circulation cells at higher latitudes (*diagram at left*). If a large, dense cloud of smoke and dust were to be introduced into the troposphere in the North Temperate Zone during these seasons, the tropospheric heating effect at the southern edge of the cloud might be intense enough to reverse the normal mid-latitude subsidence, converting the Hadley circulation into an unusual pattern characterized by a single dominant cell with upper-level winds blowing briskly across the Equator from north to south (*diagram at right*). This novel circulation pattern has been observed in sophisticated computer models of the general circulation of the atmosphere developed by investigators in the U.S. and the U.S.S.R.