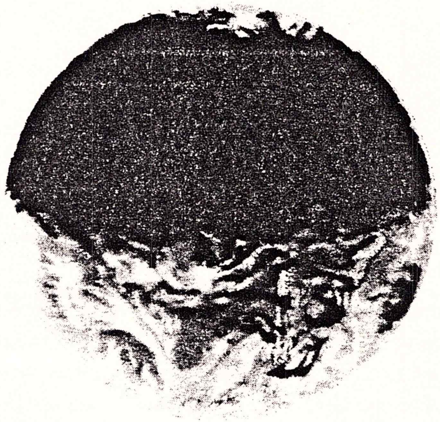

NUCLEAR WINTER

A forecast of the climatic and biological effects of nuclear war

by Anne Ehrlich

"Nuclear winter" was recently coined to describe the climatic and biological effects of nuclear war. Drawing on pioneering research in a variety of fields, a growing number of scientists believe that even a "limited" nuclear exchange would trigger a disastrous ecological reaction, and that a full-scale nuclear war might mean the extinction of our species. The seminal study by the TTAPS team, discussed in this Bulletin *supplement, is based on many models, simulations, scenarios and projections; the necessarily hypothetical nature of the findings has opened the scientists to criticism and has provoked debate. But even if further investigation should prove their "doomsday" scenario improbable, the possible consequences of any nuclear war are so horrendous as to demand our most serious attention and research. As Anne Ehrlich points out in her report below, on an issue so vital to the planet, a worst-case analysis is the only prudent approach.*

—The Editors

Appreciation is extended to the Ruth Mott Fund for its assistance in the publication of this special supplement.

NUCLEAR WINTER

by Anne Ehrlich

A NEW UNDERSTANDING of the calamitous destructive power of even a "small" nuclear conflict has begun to penetrate the world's consciousness. This awareness stems in large part from the *Conference on the World After Nuclear War,* held in October 1983, at which leading atmospheric scientists and biologists presented their findings in an environmental impact statement. In a packed hotel ballroom bristling with cameras, lights and audio equipment, the scientists described the dire conclusions of their studies and deliberations conducted over the previous 18 months.

Some presentations were highly dramatic—Carl Sagan's brief but graphic "slide show," for example—but mostly they resembled standard conference fare, low-key and unemotional. Yet if anything, the matter-of-fact tone served to underscore the horrors of the picture they were painting of the world after a thermonuclear exchange.

Unlike most scientific conferences, this one offered no controversies or disagreements. Each of the 13 speakers and panelists provided details from his own area of specialization, building on and dovetailing with all the other presentations. Piece by piece, they constructed an image of an unlivable world.

Policy statements were rigorously banned, the speakers all affirming that they would reserve their opinions on policy matters for other occasions. This event was to focus on the stark facts.

Keynote speaker Donald Kennedy, president of Stanford University, described as "most disturbing" the possibility of major climatic consequences from nuclear war "so profound that they could dwarf all of the other long-range effects described so far." While there are still many uncertainties, Kennedy warned that these findings had been carefully reviewed by many respected scientists and were much too important to be ignored by policy planners. "Our most thoughtful projections show," he said, "that a major nuclear exchange will have, among its plausible effects, the greatest biological and physical disruptions of this planet in its last 65 million years."

The possible climatic and biological effects of a nuclear war were long neglected under the assumption that they were trivial compared to the terrible immediate impacts on human populations. The World Health Organization recently estimated that a large-scale exchange might kill 1.1 billion people outright and seriously injure an equal number.[1] Nearly half of the 1984 human population thus would be immediate casualties of a nuclear war, regardless of any environmental effects. But this calamity would be only the beginning.

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Atmospheric consequences.

Carl Sagan presented the TTAPS study (named for co-authors R.P. Turco, O.B. Toon, T.P. Ackerman, J.B. Pollack and C. Sagan) on the atmospheric consequences of a nuclear war. Across a variety of scenarios (see insert and table) the TTAPS simulations produced remarkably consistent results. In a nuclear war involving both urban and military targets, thousands of detonations would inject tremendous quantities of both dust and soot into the atmosphere of the Northern Hemisphere, where the majority of likely targets are located.

The vast fires that would be ignited by attacks on cities were described by panelist Richard Turco of the TTAPS team. World War II firestorms in German cities, he warned, "presage the fierceness of the nuclear fires that might occur in modern cities, except that the nuclear fires . . . would be unprecedented in scale and much more intense, dwarfing any of the World War II conflagrations."

Within one or two weeks, the individual plumes of dust and soot would coalesce in an enormous dark cloud shrouding most of the Northern Hemisphere, particularly the mid-latitude belt encompassing most of the United States, Canada, the Soviet Union, Europe, China and Japan. Beneath the spreading clouds, very little sunlight—in the worst cases, as little as a tenth of one percent of the normal light level, averaged over the hemisphere—could reach the surface (Figure 2). Even relatively limited wars could reduce light intensities by 95 percent or more.

Clouds of dust alone would admit some light because dust particles reflect and scatter much of the light that strikes them, and some would reach the surface. Smoke clouds, by contrast, would absorb most of the solar radiation striking them, very effectively blocking out sunlight as long as they persisted.

With most of the sunlight blocked, temperatures at the surface would plummet tens of degrees, dropping far be-

The Scenarios

Case[a]	Total yield (megatons)	% Yield surface bursts	% Yield urban or industrial targets	Warhead yield range (megatons)	Total number of explosions
A. Baseline exchange	5,000	57	20	0.1-10	10,400
B. 3,000-MT counterforce only	3,000	50	0	1-10	2,250
C. 100-MT cities only	100	0	100	0.1	1,000
D. 10,000-MT maximum exchange	10,000	63	15	0.1-10	16,160
E. 5,000-MT severe counterforce only	5,000	100	0	5-10	700
F. 10,000 MT severe exchange[b]	10,000	63	15	0.1-10	16,160

In these scenarios, attacks are concentrated in the Northern Hemisphere. The 100-megaton cities-only scenario (C) assumes about a third higher smoke emission from urban fires than the other scenarios and no wildfires. "Severe" cases assume a sixfold increase in fine dust lofted per megaton of yield and a greater fraction of soot injected into the stratosphere. (*Source:* TTAPS)

[a] The cases selected from the TTAPS study have been relabeled for this article. The original TTAPS case numbers are: case A = 1, B = 11; C = 14; D = 9; E = 16; F = 17. Case Ax, shown in figure 2, corresponds to TTAPS case 4.

[b] Case F has the same parameters as D; more severe results are posited for F to show the range of possible effects following a maximum exchange.

In their atmospheric models, the TTAPS group analyzed the impacts of some 40 different scenarios on the course of a nuclear war: the numbers, sizes, altitudes, fission yield fractions, and locations of weapons detonated, as well as variations of uncertain physical parameters such as dust and soot particle size distributions, absorption coefficients and so on (see table).

The war scenarios ranged in scale from a relatively modest one involving "only" 1,000 weapons with fission yields totalling 100 megatons (one megaton is equivalent in explosive power to one million tons of TNT) detonated on 1,000 cities, to a very severe one of some 10,000 megatons expended on a variety of targets: cities, major industrial sites, missile silos and other important military installations.

The study also included a 25,000-megaton "future war" scenario, which exceeds in megatonnage the nuclear arsenals of today but will become possible if current plans for expansion are carried out. Two scenarios were given particular attention by TTAPS: a "baseline" case of 5,000 megatons, striking both military and civilian targets; and a 3,000- megaton preemptive strike on silos only, with no retaliation. The biologists focused on the 10,000-megaton "severe" scenario, wishing to apprise decision-makers of a plausible "worst case" outcome.

The kinds of targets and the altitudes of detonations make a difference in the atmospheric effects produced. A high-yield explosion on or near the surface (as most likely would be used against missile silos) tends to hurl vast quantities of very fine dust high into the atmosphere (Figure 1). Because of the stability of temperature and the low water content of the stratosphere, it is subject neither to the rapid vertical mixing nor to the cleansing effects of rain found in the troposphere (lower atmosphere). Very small particles therefore may remain in the stratosphere for long periods—on the order of a year.

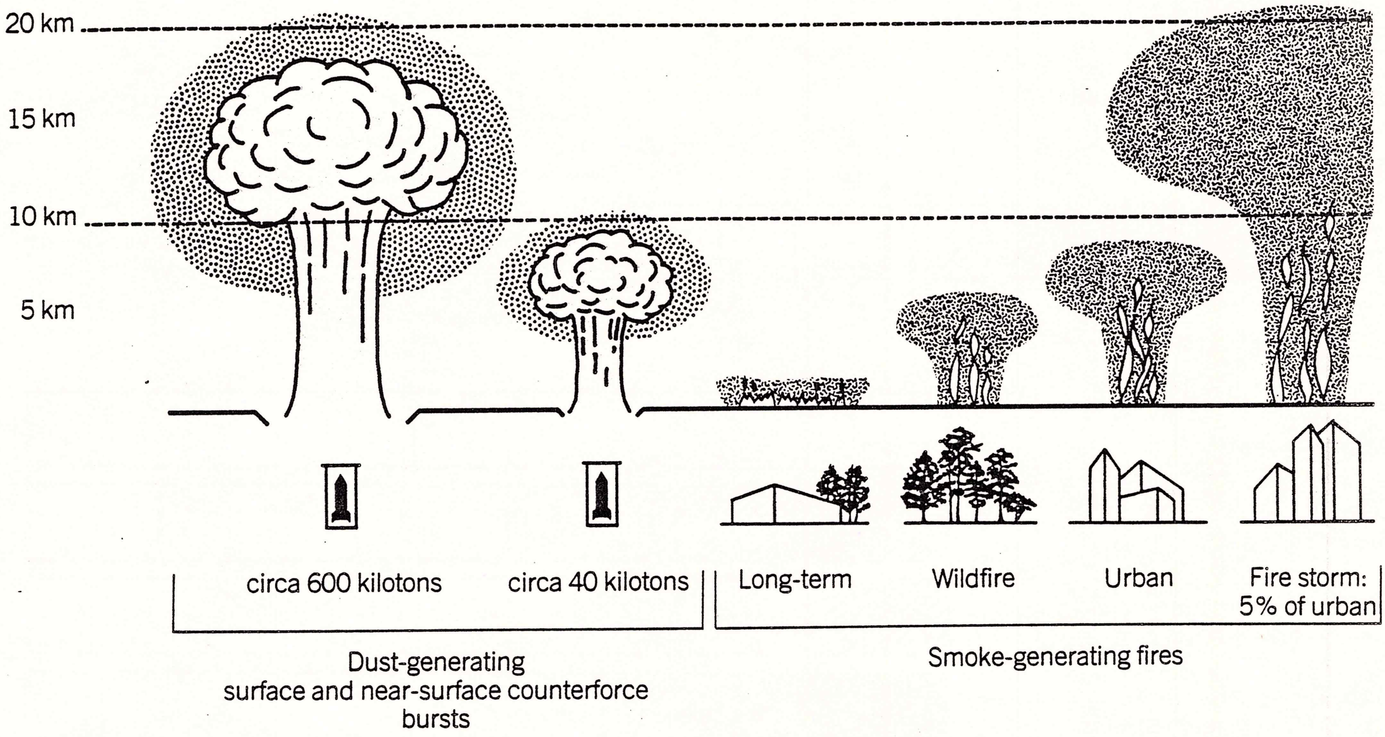
While it is uncertain exactly how much dust would be injected into the stratosphere by nuclear detonations, research from nuclear bomb tests indicates a range of roughly 100,000 to 600,000 tons of dust per megaton of yield. Most of the TTAPS scenarios specified production of 330,000 tons of stratosphere dust per megaton exploded in surface bursts and 100,000 tons per megaton in near-surface bursts. The "severe" scenarios were calculated with more adverse, but still plausible, parameters for dust injections.

Large numbers of lower-yield air bursts, which probably would be used to inflict maximum damage on cities, would ignite huge fires and deposit enormous quantities of smoke and soot in the troposphere, where they would linger for many weeks. Under normal conditions of air movement the soot particles would gradually settle out of the atmosphere or be removed in precipitation.

The quantities of smoke that would be produced by nuclear detonations are even more uncertain than those of dust. The baseline scenario conservatively assumed partial burning of about 240,000 square kilometers of urban area and total burning of 500,000 square kilometers of forest, brush and grassland area, producing altogether about 225 million tons of smoke particles—roughly equivalent to a year's normal worldwide smoke emissions—within a few days. Their particular composition and their persistence, however, give them a far greater capacity to perturb the atmosphere.

At the Conference, panelist John Holdren of the University of California at Berkeley confirmed the credibility of the TTAPS war scenarios, pointing out their similarity to reference scenarios in other recent studies of the consequences of nuclear war. The baseline case, he noted, "involves the use of about a third of the total [nuclear] inventories, or about a half of the strategic inventories altogether." Even the 10,000-megaton severe case was plausible under very adverse circumstances, such as a small conflict escalating from battlefield weapons to use of the full strategic arsenals.

Figure 1.
Deposit of particles in atmosphere



The graphs which accompany this article were developed by Michael Yanoff, who heads the graphics department of a Chicago financial institution. He has done research, lectured, and led design seminars on the communication of technical information.

low freezing in continental interiors a week or so after the exchange, whatever the season. Extremely cold temperatures would last for many weeks, even months, returning to normal only very slowly (Figure 3). Coastal areas and islands would be spared the extreme cold by the moderating influence of the oceans' vast thermal inertia. But the huge temperature difference between the oceans and the continental interiors would subject coastal areas to months of unremitting violent weather.

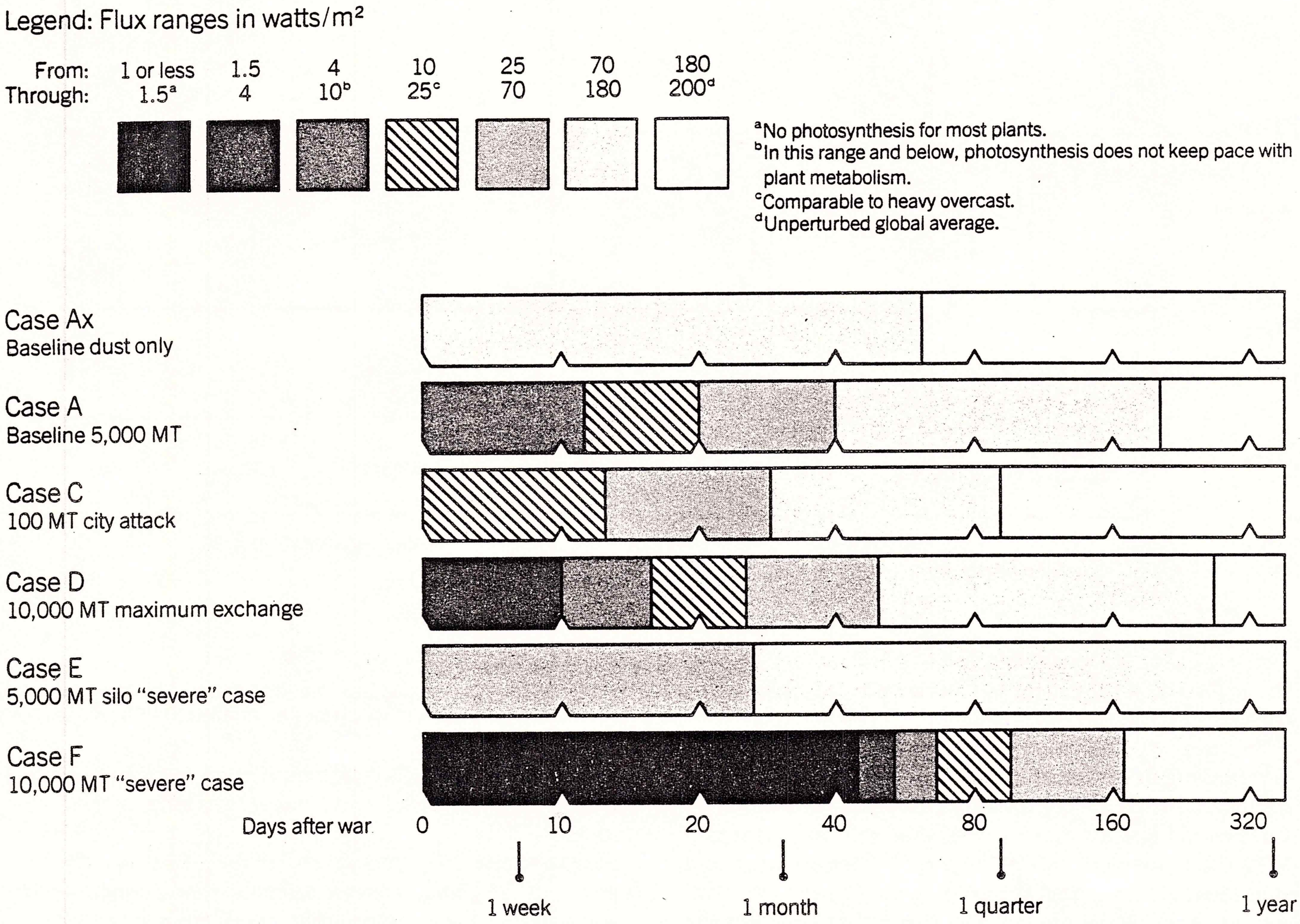
How far temperatures fell and how long they remained significantly below normal would depend on the details of the conflicts and the actual values of the uncertain physical parameters. Obviously, the largest numbers of weapons would produce the worst effects. The 10,000-megaton "severe" scenario could plunge average surface continental temperatures in the northern mid-latitudes to around minus 50 degrees centigrade and keep them below freezing for a year or longer.

Yet surprisingly harsh and lasting effects could be generated even by relatively modest exchanges. The baseline scenario (5,000 megatons) could drop average continental temperatures in the Northern Hemisphere to about minus 23 degrees centigrade. Shockingly, even 100 megatons detonated on cities alone could produce sufficient smoke to blacken skies and chill continental areas to below minus 20 degrees centigrade, with recovery taking over three months.

Sagan stressed the "robustness" of these findings: "If 0.8 percent of the global strategic arsenals were dropped—100 megatons on 1,000 cities—that would trigger an effect about as bad as the 5,000 megaton case. In other words, these climatic results are very independent of the kind of war we're talking about. And there is a rough threshold of 100 megatons, more or less . . . at which this climate effect can be triggered." He also emphasized that any attack above that "threshold" would be suicidal, regardless of retaliation.[2] As panelist Stephen Schneider noted wryly, an attacker would "win" for only about two weeks.

The extent to which these severe atmospheric effects might spread from the northern mid-latitudes to the tropics or even to the Southern Hemisphere remains uncertain, but TTAPS and other studies using different kinds of models indicate that such propagation is very possible.[3] Schneider offered preliminary results of the National Center for Atmospheric Research (NCAR) study, using a three-dimensional model, which indicated fairly rapid transport of aerosols to the Southern Hemisphere. So did the model used by the Soviet Academy of Sciences, as reported by Soviet

Figure 2.
How dark: Solar energy flux at ground level



Solar energy fluxes at ground level, averaged over the diurnal cycle and the Northern Hemisphere, from selected TTAPS scenarios. (Source: TTAPS)

scientist Vladimir Aleksandrov. If they are right, the atmospheric effects—the cold and the darkness—of a nuclear war would engulf the entire globe.

In most respects, both the NCAR and Soviet studies confirmed the TTAPS results. "Everything we've seen so far," Schneider said, "suggests that, although the details do vary . . . the basic picture [is] very hard to get rid of." Turco and other speakers nevertheless stressed the continued uncertainty on details of the atmospheric effects despite the general agreement.

A point emphasized in the Soviet study was that normal precipitation might be suppressed by the dust-laden, warmed atmosphere following a nuclear conflict. The Soviets also found that, as the solar-heated soot clouds cleared, surface temperatures could become much *warmer* than normal—as much as 25–35 degrees centigrade above average—in continental interiors. (But this effect may well be an artifact of the model, in which soot clouds dissipate suddenly rather than gradually over months.)

BEYOND the "nuclear winter," the TTAPS study found that massive burning of synthetic materials in urban and industrial areas would release—besides smoke—a deadly mix of toxic fumes (labeled "pyrotoxins" by TTAPS) such as carbon monoxide, oxides of nitrogen, ozone, cyanides, dioxins and furans, to blanket much of the Northern Hemisphere for months.

TTAPS also confirmed earlier findings that a nuclear war could cause destruction of stratospheric ozone, allowing penetration of radiation in the ultraviolet-B range. While the smoke and dust clouds persisted, they would absorb most of the ultraviolet-B, but the ozone shield would be reestablished more slowly. Thus, clearing skies would expose Earth's surface to the damaging radiation for some years.

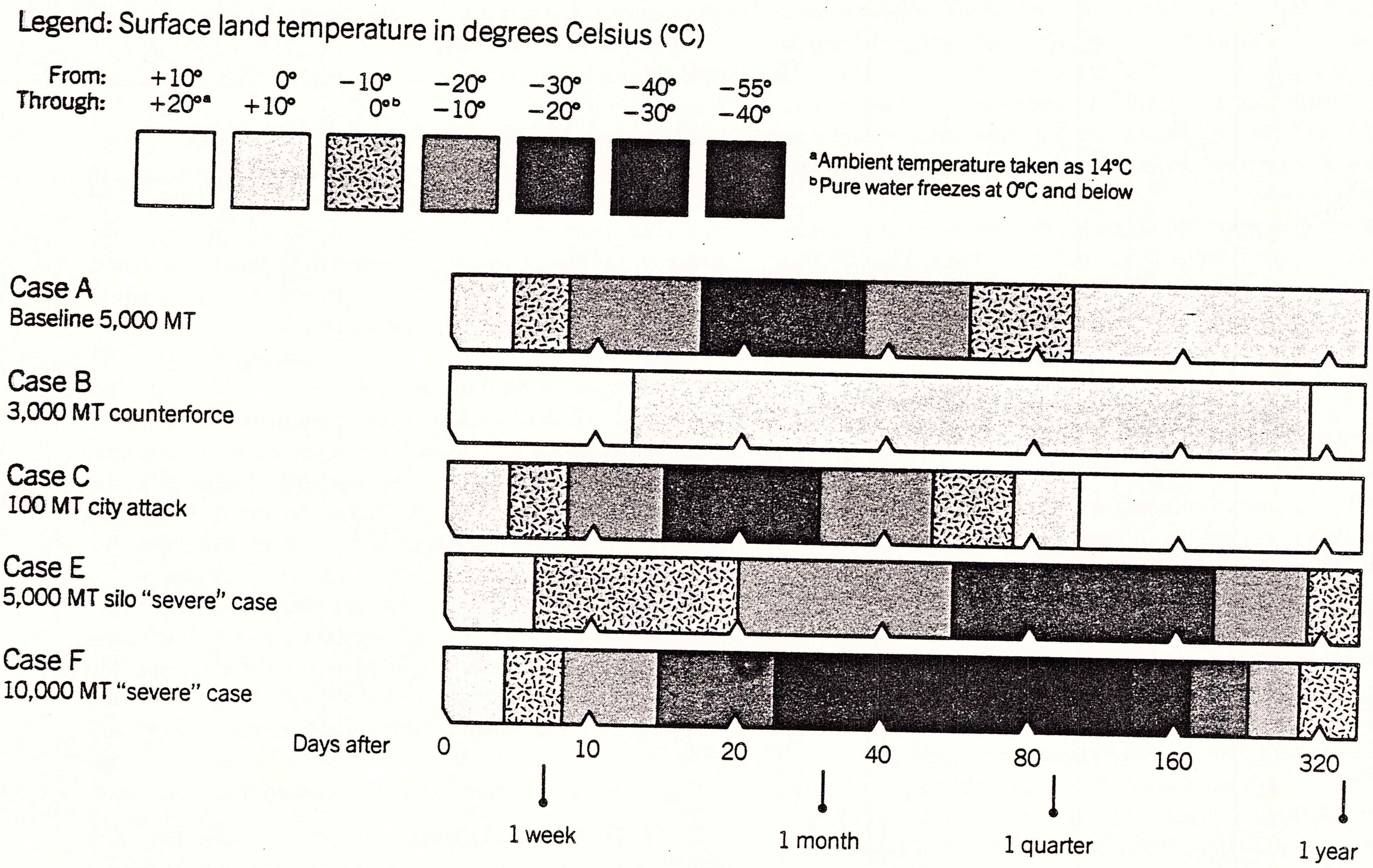
The baseline scenario projects a reduction of ozone concentrations of up to 30 percent, averaged over the Northern Hemisphere. This would produce ultraviolet-B exposures at the surface roughly twice the normal level after cloud dissipation. Higher megatonnage wars would produce relatively greater depletion of the ozone shield—twice as much for a 10-megaton exchange, for instance.

In addition, the TTAPS report included new predictions on the distribution and, especially, the timing of radioactive fallout. Previous studies, based on high-yield test explosions, had focused on immediate and long-term fallout. But they had neglected medium-term fallout, that occurring between a few days and a few months after a nuclear exchange. Virtually everyone exposed to immediate lethal doses of radiation from fireballs would be killed by blast and heat. Prompt fallout (within a day or two) also would be largely confined to target areas. Earlier intermediate and long-term radiation estimates rested on the generally unspoken assumption that most radioactive debris would be injected into the stratosphere where it would remain for one to two years. By then, most of the radioactive elements, which are fairly short-lived, would have decayed to relatively harmless levels.

Calculations by the TTAPS team, however, indicated that the medium-term component, mainly from rapid washout

Figure 3.

How cold: Temperature at ground level



Temperature trends for Northern Hemisphere interior land areas, averaged over all latitudes and seasons, for selected TTAPS scenarios. "Counterforce only" scenarios involve only military targets, no cities; hence no smoke is produced. The effects in such scenarios are all from stratospheric dust. (Source: Carl Sagan) and fallout of radioactive debris deposited in the troposphere by low-altitude and ground-level bursts, might be substantial. Thus, for a conflict of any given size, the average exposure to survivors far from targets might be increased by an order of magnitude over earlier estimates. Panelist John Holdren compared these new findings to those of another recent study conducted at the Lawrence Livermore Laboratory. Both studies had revealed the likelihood of considerable intermediate-term fallout, which would, as he put it, "contribute rather nastily to the total dose."

For the baseline case, the average medium-term, whole-body, external dose of gamma emissions to unsheltered people in the Northern Hemisphere could be about 20 rad. The average dose in the northern mid-latitudes might be 50 rad, and exposure to local "hot spots" and internal doses from food could easily add another 50 rad. A great many individuals, especially downwind of major targets, would receive far greater than average doses.

Average doses of 100 rad or so imply serious problems for an exposed population, especially in the probable absence of even minimal medical care and with simultaneous exposure to numerous other severe stresses. With adequate medical care, the whole-body radiation dose that would kill half of the exposed healthy adults is thought to be about 350 to 500 rad if received in 48 hours or less. Under adverse conditions, the lethal dose might be much lower. If so, at least half of the surviving populations of combatant nations in a nuclear war of even moderate size could be exposed to life-threatening doses of radioactivity in the aftermath, and nearly everyone could suffer some resulting illness.

A nuclear conflict involving greater megatonnage would produce proportionately larger radiation doses. The 10,000-megaton severe scenario in the TTAPS study might result in exposures of about 500 rad over 30 percent of the Northern Hemisphere land areas, killing at least a half-billion people.

QUESTIONS from the audience dealt with several other points:

• Why the climatic consequences had not been discovered before was unanswerable. The basic physics and chemistry had been available for 20 years, and governments had a responsibility to study them.

• Whether massive disruption of the hydrological cycle would cause torrential rains and heavy erosion was difficult to predict. In the absence of sunlight, evaporation would be sharply reduced, thus possibly diminishing the moisture content of the atmosphere and suppressing precipitation.

• Could these discoveries be made public in the Soviet Union? Golitsyn replied that some aspects of his work had already been published in the proceedings of the Soviet Academy of Sciences.

Biological consequences.

"The environment that will confront most human beings and other organisms will be so altered and so malign that extreme and widespread damage to living systems is inevitable," declared Paul Ehrlich, who presented the biologists' consensus on the biological implications of the TTAPS discoveries.

The reduction of sunlight by more than 95 percent for several weeks would represent a severe assault on green plants—the foundation of all significant ecosystems. Virtually all animals, including human beings, are directly or indirectly dependent on the energy green plants capture from sunlight in the process of photosynthesis.

Panelist Joseph Berry, a plant ecologist at the Carnegie Institute, reminded the audience that photosynthesis is the "major . . . energy input in the biosphere . . . the driving force for the operation of natural and agricultural ecosystems." In most plants, photosynthetic activity is proportional to the amount of light they receive, and 15 percent or more of the energy fixed is needed to maintain life processes. If light falls below that point, plants begin to "consume themselves," and animals also consume them. A severe loss of light thus means loss of biomass.

Under the smoke-shrouded skies of a nuclear winter, for several weeks light intensities would be too low to permit growth in most plants. The 10,000-megaton "severe" case could turn midday into the equivalent of a moonlit night for many weeks—too dark for any photosynthesis at all—and complete recovery to pre-war light levels would take more than a year.

The darkness, drastic in itself, would be accompanied by plummeting continental temperatures. Growing plants are as sensitive to temperatures as they are to light intensities; even quite small changes can make significant differences. A reduction in average temperatures of one degree centigrade at critical times can reduce corn crop yields by as much as 10 percent, for example.

Temperatures far below freezing during the growing season would annihilate annual plants, including most crops, and kill or severely damage even the hardiest perennials. Even normally cold-tolerant species, such as winter wheat and deciduous trees, need time to acclimate to winter cold. More sensitive plants, including many important crops, could be seriously harmed by low temperatures that only *approached* freezing during the growing season.

Moreover, the effects of cold and darkness would interact synergistically, each intensifying the other. Cold-damaged plants need abundant sunlight to repair the damage, and the rate of photosynthesis is retarded by low temperatures. Plants in the tropics and subtropics are particularly vulnerable; if the climatic effects spread southward, both crops and natural vegetation in those regions would be devastated.

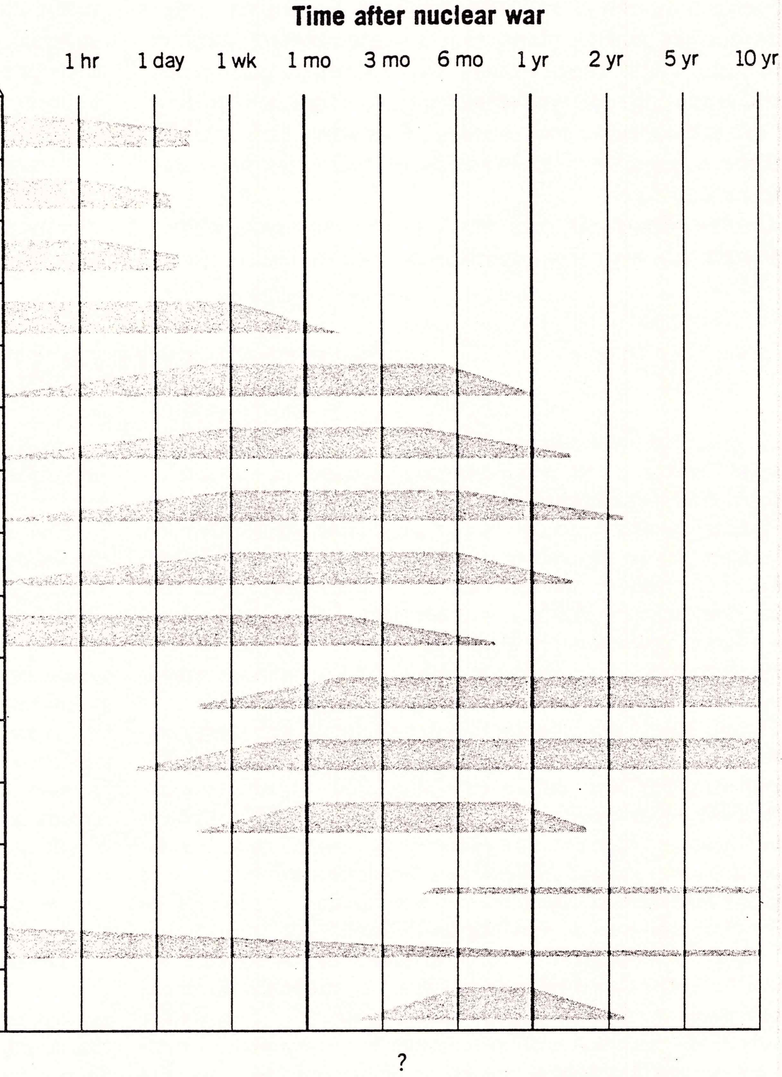
EXTREME COLD and darkness would also have disastrous impacts on animals. In seasons that are normally warm, animals would be especially vulnerable to sub-freezing temperatures. Hibernating animals need a full summer's buildup of fat reserves to last through a normal winter, let alone a protracted, super-cold nuclear winter. Herbivores

Figure 4.

Timing and magnitude of effects of baseline nuclear war

Population at risk

Effect	US–Soviet Union	Northern Hemisphere	Southern Hemisphere	Potential deaths, globally	Total casualties
Blast	H	M	L	H	M-H
Thermal radiation	M	M	L	M	M-H
Prompt ionizing radiation	L	L	L	H	L-M
Fires	M	M	L	M	M
Toxic gases	H	M	L	L	L
Darkness	H	H	M	L	L
Cold	H	H	H	H	M-H
Freezing of water supplies	H	H	M	M	M
Fallout of ionizing radiation	H	H	L-M	M	M-H
Food shortages	H	H	H	H	H
Medical system collapse	H	H	M	M	M
Contagious diseases	M	M	L	H	M
Epidemics & pandemics	H	H	M	M	M
Psychiatric disorders	H	H	L	L	L-M
Increased surface ultraviolet light	H	H	M	L	L
Synergisms	?	?	?	?	?



H = high, M = medium, L = low. For global deaths, L = less than 1 million, M = 1 million to 1 billion, H = more than 1 billion. (Source: Mark Harwell, Carl Sagan)

would starve and their deaths would deprive carnivores of food. Lacking human care, domestic animals would be in similarly desperate straits; most would soon perish.

Thirst would be another problem. Panelist John Harte, of the University of California, has calculated that ice, one to two meters thick, would form on inland surface waters. If precipitation were reduced as well, people and farm animals would die of thirst—one more malign synergism. "It's interesting how synergies seem to work with you when things are going well," he remarked, "and they turn against you when you and nature are down."

Aquatic ecosystems, sometimes thought to be a potential source of food for human survivors of a nuclear war, would also suffer. Marine phytoplankton, the photosynthesizing base of marine ecosystems, are highly susceptible to prolonged darkness; their disappearance would quickly lead to starvation of animals higher in marine food chains. These systems moreover would be inundated by runoff from shore of toxic compounds released from ruptured storage and industrial facilities and of silt from denuded, burned-over lands. And the violent storms likely to prevail along coasts would make harvesting any surviving sea life difficult if not impossible.

Ionizing radiation would be an additional threat to all forms of life. Most birds and mammals are nearly as sensitive to radiation as are human beings. Sensitivity varies substantially among plants but is higher among conifers and some crops. Fallout could kill or damage millions of trees, rendering forests susceptible to wildfires, and adding to the atmospheric soot burden. Radiation also inhibits photosynthesis, an effect exacerbated by low temperatures and lack of light.

George Woodwell, moderator of the biological panel, reported that his early experiments with radiation effects on forests had indicated biotic impoverishment and quicker recovery of species with short life cycles and high reproductive potential, namely, pests. He emphasized the central importance of forests in the biosphere; their destruction would cause an enormous acceleration of extinctions. A postwar world would contain few forests; they could quickly be destroyed, but very slowly replaced.

When skies cleared, ultraviolet-B radiation, admitted at twice or more pre-war levels, could significantly affect virtually all organisms. It can reduce productivity in plants, especially under low light conditions, and might severely disrupt oceanic food webs. In mammals, ultraviolet-B can suppress immune systems, as can ionizing radiation, and cause visual damage and blindness.

Persistent darkness, below freezing temperatures, ionizing radiation, toxic air pollution, widespread fires and completely unpredictable, possibly extreme weather are each capable of causing disasters. The combined assaults of *all*

Soviet participation

A highlight of the events was the "Moscow Link," in which a dialogue between Soviet and American scientists was shown via closed-circuit satellite video on large screens to audiences in both Washington and Moscow immediately after the Conference. Representing the Americans were Thomas Malone, Paul Ehrlich, Walter Orr Roberts and Carl Sagan; the Soviet spokesmen were astronomer Evgeny Velikhov (vice president of the Soviet Academy of Sciences), meteorologist Yuri Izrael, geneticist Aleksander Baev and physician Nikolai Bochkov. Unlike the Conference proceedings, this exchange ventured into the policy arena.

Sagan briefly outlined the findings of the TTAPS study, emphasizing the consistency of atmospheric consequences even in "rather modest" scenarios, such as the 3,000–megaton counterforce war which could produce effects severe enough "to wipe out the wheat- and corn-producing areas of the United States, Canada, and the Soviet Union." The resultant "set of simultaneous assaults on the biosphere of unprecedented magnitude . . . must follow a nuclear war even of relatively small yield."

Sagan declared that "the combined arsenals of the United States and the Soviet Union [are] many times . . . above the threshold [that could produce catastrophic climatic effects]. . . . Since the early 1950s, the leaders of both nations have been making decisions on world affairs in ignorance of the possible, very dire climatic consequences of the use of nuclear weapons."

Paul Ehrlich summarized the unanimous conclusions of a large group of distinguished biologists on the implications of the TTAPS results for biological systems. With simultaneous exposure to the cold, darkness, fallout, toxic air pollution and increased ultraviolet-B, "the basis of the planet's productivity, at least in the Northern Hemisphere, [would have] been hit by a series of assaults, *any one of which* would be extraordinarily damaging."

A large-scale war would halt agricultural productivity for at least a year, destroy most stored food supplies and freeze inland water sources. "In general, [biologists] can see nothing but a collapse of the life-support systems, at least in the temperate zone of the Northern Hemisphere—a situation in which any sort of survival of civilization . . . would be difficult or almost certainly impossible. . . . The biological results were obvious and very robust for the whole range of scenarios."

While the extent to which the climatic effects would spread to the Southern Hemisphere was uncertain, Ehrlich said, they were virtually certain to reach the northern tropics, resulting in destruction of some tropical forests— the greatest reservoir of organic diversity on the planet. Survivors in the Southern Hemisphere would be "faced with a situation that would be entirely unprecedented [and] extremely malign."

The Soviet scientists presented their findings, which generally confirmed those of TTAPS, with a few, relatively minor, differences. Yuri Izrael noted that human industrial activity "has already led to a number of ecological and global problems arising. It is quite obvious that, in the case of a nuclear war, the biosphere will be even more affected by many orders of magnitude and [this] will lead to catastrophic results for humanity and for the biosphere as a whole."

Izrael related that the Soviets had found that only about one percent of the dust and soot lofted into the atmosphere by a nuclear exchange would persist more than two weeks, but even this could produce disastrously low surface temperatures. The Soviets furthermore projected a possible later *rise* in surface temperatures because of the absorption of outgoing infrared radiation by the aerosols and by "gaseous admixtures"—ethane, methane and so on—including a doubling of carbon dioxide concentrations. These pollutants could increase surface temperatures by about three or four degrees centigrade, a "hothouse effect" that would cause the "practical destruction of agricultural activity." The combined synergistic effects would affect not only the "warring factions" but others as well. There would be no victors: "In the final analysis, all sides suffer fatally."

Aleksander Baev asserted that nuclear war was immoral and the loss of human lives—as many as half of the entire human population—would be unacceptable. For the survivors, "their continued existence will be difficult and problematic." At best, peoof these, occurring simultaneously or in rapid succession over weeks or months, followed by more months of exposure to enhanced ultraviolet-B radiation, would have catastrophic, often synergistically amplified, effects on both natural and agricultural ecosystems. (See Figure 4 for the relative timing of individual effects.)

Joseph Berry noted ominously that, over geologic time, global photosynthetic productivity has been remarkably constant, varying only about 5 percent. The devastation of plant life caused by a nuclear winter could cut photosynthesis in the Northern Hemisphere by 80 to 90 percent in the first year. Because of the sharp reduction in biomass and the retarding effects of ultraviolet-B on growth, restoration of productivity to normal levels would be very slow.

Uncountable populations of plants and animals throughout the Northern Hemisphere would be obliterated; their disappearances would reverberate through ecosystems as the loss of one population led to the eradication of others dependent on it. In subtropical and tropical regions, where species diversity is far richer, but where most organisms are less able to tolerate loss of light and warmth, the cascade of extinctions could reach proportions unequalled since the dinosaurs disappeared at the end of the Cretaceous period. Even if climatic conditions returned essentially to normal within a year or two, ravaged ecosystems would require far longer to recover a semblance of their former productivity and stability—possibly millenia.

THE VITAL SERVICES that natural ecosystems provide in support of humanity depend on their productivity and stability.[4] Those services include maintenance of the quality and composition of the atmosphere, moderation of climate and weather, regulation of the hydrological cycle, cycling of nutrients (including those needed in agriculture), disposal of wastes, replenishment of soils, pollination of

ple "will survive only as small islands in a lifeless and hostile environment." Nikolai Bochkov stated that the study of the consequences of nuclear war was a most important task for all biologists: "We [Soviets] are optimists," he said, "and hope that humanity will give up any thought of using nuclear weapons." The Soviet study had shown a massive breakdown of normal atmospheric circulation patterns, following which "all the dirt from the north will wander" to the Southern Hemisphere and "on the globe, there will be no place to be found that will not experience all the consequences of such a nuclear conflict."

From the Moscow audience, K. Kontratyev, an atmospheric physicist at the University of Leningrad, spoke up on one more atmospheric effect: extrapolations from nuclear tests in 1961–1962 indicated that stratospheric additions of nitrogen dioxide would strongly absorb solar radiation, producing a surface cooling of 9.5 degrees centigrade in a full-scale war. Gaseous nitrogen dioxide would persist far longer in the stratosphere than would dust particles, thus inflicting on the Southern Hemisphere the same dire consequences, he claimed. Other scientists, however, were dubious about this possibility.

As a scientist, Sagan was gratified that Soviet and U.S. scientists had independently reached such similar conclusions, but noted lingering uncertainties about scenarios chosen, amounts of soot and dust lofted, particle agglomeration, residence times, changes in atmospheric circulation and radiation doses. He asked: "Do our Soviet colleagues think it possible that they might supply data on the particle size distribution function of debris from the Soviet nuclear tests before the 1963 Limited Test Ban Treaty? And information on particle sizes and absorption coefficients from large fires in the Soviet Union? And also will they eventually give us the range of nuclear war scenarios that they consider likely?"

After a tense pause, Izrael responded. "Our dialog . . . should be continued, probably during meetings of scientists at conferences. . . . I also have many questions for my American colleagues on the initial data that they used in constructing their models." Other Soviet scientists expressed agreement on the importance of further cooperation and collaboration.

Ehrlich thanked Bochkov for bringing up the matter of long-term genetic effects from radiation. Increased cancers and birth defects, compounded by the effects of inbreeding, could burden future generations. Genetic damage would also be inflicted on natural ecosystems by both radioactive fallout and ultraviolet-B radiation. Because of the unknown extent of this damage, in addition to all the other assaults which would create an entirely new set of selection pressures, it was impossible to predict how these systems would recover. Surviving groups of people would be facing a totally new environment bereft of any useful cultural resources to help them cope with it.

G.K. Skryabin, General Science Secretary of the Soviet Academy, spoke of his "feeling . . . about the possible tragedy that cannot but worry and bring concern to any normal human being." But he also commented that "our American colleagues and Russian scientists . . . here are unified in their view that there should be no nuclear war, that this means disaster and death for mankind. The authority of scientists is very great . . . we should all try to bring our influence to bear in order to bring about an end to the arms race so there will never be a nuclear war."

Ehrlich responded: "All of us over here share that wish most devoutly. . . . Not only is the East/West confrontation threatening to the Soviet Union and the United States and their direct allies, but it is also threatening every human being on the planet *at least* with grave injury and, probably for almost everyone, death. This has got to form the background for the policymakers of the world." Thomas Malone added that in future years the Conference might be viewed as a "turning point in the affairs of man."

"The only conclusion possible here," Velikhov said, "is that nuclear devices are not and cannot be a weapon of war . . . or a tool of politics. . . . Nuclear superiority is a delusion. . . . Nuclear arms are not muscles of [the] modern state; they are a cancerous growth which threatens the very state. . . . Either we will destroy the cancerous growth or [it] will destroy us."

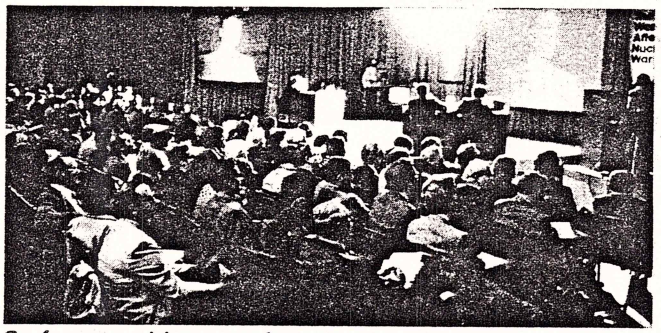
Finally, Walter Orr Roberts expressed the hope that the scientists all could collaborate in efforts "to reduce the uncertainties. . . . But we already know enough to realize that it's imperative, in the name of all humanity, to accelerate the search for world security in the policy domain, as well as in the scientific domain. And, as citizens of our own nation-states and as residents of this fragile spaceship Earth, we must invent and enact new policies that covenant a stable future for that planet and for all of its people."

crops, and a vast "genetic library" from which society has already drawn the very basis of civilization.

The loss or severe disruption of those services would inevitably follow the massive destruction of natural ecosystems by a nuclear war—just when human populations needed them most. John Harte vividly explained: "All of us on Earth are dependent on the ecosystems surrounding us as an intensive care patient is on I-V bottles and life-supporting medical equipment. Waging nuclear war would be akin to throwing a stick of dynamite into an intensive care ward, rupturing the vital links that ensure survival." Thomas Eisner of Cornell University noted the difficulty of preparing a detailed environmental impact statement for nuclear war, because biological systems are extremely complicated and still poorly understood; the impacts would be all-encompassing; and recovery from such a host of massive assaults would be slow, compounded by synergisms.

Like natural ecosystems, agricultural and other managed systems would be devastated. Any farmers still able to farm would be cut off from supplies of seeds, fertilizer, pesticides, and fuel. Starving animals, domestic or wild, might invade fields in search of food, and pests would proliferate unchecked. At least in the northern mid-latitudes, agricultural production in the first year after a nuclear war of significant size would be essentially nil, and it would be problematic for subsequent years. Modern agriculture as practiced today in developed countries would probably never be seen again. Panelist Mark Harwell of Cornell University noted that human survivors would therefore be dependent on natural ecosystems for sustenance, an additional

About the Conference



Conference participants watch monitor screens with images beamed via satellite to Moscow.

The Conference on the World after Nuclear War, born a few years ago, resulted from a confluence of interests among environmentalists, some scientists and a handful of foundation executives, who realized that existing studies of the environmental consequences of nuclear war were appallingly deficient.

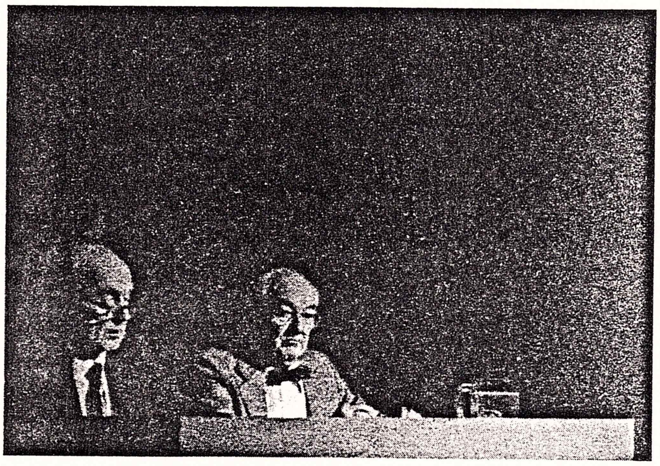
Although immediate impacts on human populations from blast, heat, fires and radiation were well known, the only long-term effect that had received much attention before the early 1970s was radioactive fallout.[1] Then came the discovery that large quantities of oxides of nitrogen generated by high-yield fireballs could rip gigantic holes in the protective ozone shield in the upper atmosphere, allowing greatly increased amounts of light in the ultraviolet-B range to reach Earth's surface.[2]

The possibility that nuclear war could have drastic effects on climate attracted serious attention for the first time in 1982. The first quantitative study of the impact on Earth's atmosphere from smoke generated by fires in a nuclear war appeared in an article in *Ambio* by Paul J. Crutzen of the Max Planck Institute in Mainz and John W. Birks of the University of Colorado.[3] Crutzen, a panelist at the Conference, related that he and Birks had focused mainly on the destruction of ozone by oxides of nitrogen in the stratosphere; but they also looked into the quantities of smoke that would be produced by fires, and their calculations indicated that sunlight would be substantially blocked from reaching the surface for many weeks in the Northern Hemisphere.

Cornell astronomer Carl Sagan, whose interest had been piqued a decade earlier by observations of a giant dust-storm on Mars, saw the implications of the article by Crutzen and Birks. Sagan and colleagues Richard P. Turco, of R & D Associates, Marina del Rey, California, and O. Brian Toon, Thomas P. Ackerman and James B. Pollack of NASA further investigated the impacts of the dust and smoke that would be injected into the atmosphere by a large-scale nuclear war, using physical models of Earth's atmospheric circulation. They summarized their findings in early 1983 in a 120-page manuscript entitled "Global Atmospheric Consequences of Nuclear War." (The group's surname initials formed the acronym which led to the study being dubbed "the TTAPS Report.")

For years, Stanford biologist Paul Ehrlich had been writing and speaking about environmental consequences of nuclear war, which previous studies had largely neglected. In 1982, when he circulated for review a manuscript on that subject to other interested ecologists and evolutionists, two of them suggested he send it to Carl Sagan.[4]

Around that time, a group of environmentalists and foundation people, who realized that nuclear war posed the ultimate, though generally unrecognized, environmental threat, were planning a conference on the "Long-Term Worldwide Biological Consequences of Nuclear War" to be held in late 1983. The three groups, on learning about each others' efforts, decided to collaborate in developing and confirming the new information on



Thomas Malone (left) and Walter Orr Roberts.

pressure that would surely delay the recovery of those systems.

Impacts on the human population.

Human survivors of a large-scale nuclear conflict would face a dark, swiftly chilling, radioactive, smoggy world in which most of the social services we take for granted—medical care, food and water distribution systems, centralized heat and power supplies, communications and so on—had completely broken down. Cities and industries would be in ruins; surface water supplies would quickly run out; and no assistance from the outside could be expected.

The few healthy survivors would be burdened by masses of corpses and seriously injured friends, neighbors and relatives needing care. In the absence of functioning sanitation systems and medical care, diseases would flourish in a population weakened by exposure, radiation and malnutrition. The psychological burdens can be only dimly imagined.

Apart from the difficulties of keeping warm, finding unfrozen water, and avoiding radiation exposure and the choking smog, food would be the most urgent need. The war undoubtedly would have destroyed much food in storage as well as crops in the fields. Worldwide food production rarely is abundant enough to provide carry-over stocks that would last for more than two months under normal consumption patterns.

Only grains are stored in large quantity, usually far from population centers. Thus any grain that escaped destruction would be largely inaccessible. Without agricultural produc-

Paul Ehrlich (left) and Carl Sagan.

climatic effects and to present it to the public at the conference. Ecologist George Woodwell of the Marine Biological Lab at Woods Hole, Massachusetts became chairman; Chaplin Barnes of the Audubon Society was executive director. Sponsorship by a consortium of environmental, scientific, educational and other public interest organizations was obtained, as well as financial support from foundations and individuals.

In April 1983, two preliminary meetings in Cambridge, Massachusetts were attended by over 70 distinguished physical scientists and biologists. The TTAPS study was presented first to the physical scientists, who had numerous questions about details but very little quarrel with the findings. Several of the scientists went home resolved to try the scenarios on *their* atmospheric models—among them Stephen Schneider of the National Center for Atmospheric Research and Vladimir V. Aleksandrov of the Soviet Academy of Sciences Computer Center, the only Soviet scientist able to attend the meeting.

The biologists then examined the consensus results of the physicists. They too had many questions about details of the atmospheric findings but essentially no disagreement on the impacts of anything resembling the TTAPS effects on biological systems, agriculture or human life.

During the spring and summer, the TTAPS paper was refined in the light of reviewers' comments while 20 of the biologists prepared a manuscript on the long-term biological consequences of the atmospheric changes forecast by TTAPS.[7] Both papers were submitted to *Science*, to be published soon after the meeting which now bore a less cumbersome name, "The Conference on the World after Nuclear War."[5] Meanwhile, preliminary results had begun to emerge from other atmospheric studies being conducted at the National Center for Atmospheric Research, the Soviet Academy of Sciences and Lawrence Livermore Laboratory.[6] These findings were also incorporated into the Conference presentations.

The 700 remarkably diverse participants who attended included dozens of scientists as well as people from foundations; from the 31 sponsoring organizations and other public interest groups; from religious, educational and medical institutions; from the press, the U.S. government and several other governments; and from businesses as disparate as Lockheed and Random House.

1. J. Peterson, ed., *The Human and Ecological Consequences of Nuclear War* (New York: Pantheon, 1983).
2. National Academy of Sciences, *Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonations* (Washington, D.C.: 1975); Office of Technology Assessment, *The Effects of Nuclear War,* (Washington, D.C.: 1979).
3. *Ambio,* 11, nos., 2–3 (1982), pp. 114–25.
4. Published as a chapter in Jennifer Leaning and Langley Keyes, eds., *The Counterfeit Ark* (Cambridge, Massachusetts: Ballinger, 1983).
5. R.P. Turco, O.B. Toon, T.P. Ackerman, J.B. Pollack and C. Sagan (TTAPS), "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," *Science,* 222 (Dec. 23, 1983), pp. 1,283–92; P.R. Ehrlich and others, "Long-Term Biological Consequences of Nuclear War," *Science,* 222 (Dec. 23, 1983), pp. 1,293–1,300.
6. C. Covey, S.H. Schneider and S.L. Thompson, "Global Atmospheric Effects of Massive Smoke Injection from a Nuclear War: Results from General Circulation Model Simulations," *Nature* (submitted); V.V. Aleksandrov and G.L. Stenchikov, "On the Modelling of the Climatic Consequences of the Nuclear War," USSR Academy of Sciences, Computing Center, The Proceeding on Applied Mathematics (Moscow: 1983); J. Knox, *Report UCRL–89907,* Lawrence Livermore Laboratory (1983).

tion, even a heavily decimated population would face severe and continuing food shortages in a short time—although they would be alleviated somewhat in developed countries by the disappearance of livestock as competitors for grains.

Many European countries, Japan, and often the Soviet Union are deeply dependent on food imported mainly from North America, as are numerous developing nations. Shipments of food and other commodities obviously would halt immediately, throwing many regions into almost instant famine. In the sub-tropics and tropics, people might turn in desperation to the remaining forest areas, try to convert them to subsistence agriculture, and thereby greatly accelerate the already disastrous current rate of tropical deforestation, compounding the destruction caused by the atmospheric disturbances.

In the northern target regions, it is unlikely that more than a tiny fraction of the original population could survive the first few months after a nuclear war of appreciable scale. Even though atmospheric conditions might return more or less to normal in a few years, other aspects of the environment would be altered beyond recognition. Ecosystems would recover slowly, with entirely new structures, impoverished species compositions and a reduced capacity to support human life. Local climates would probably be novel and unpredictable. Pre-war cultural adaptations would be useless in such a changed, hostile, unstable world.

THE FAMILIAR complex technological civilization that supports us doubtless would be shattered beyond repair. Once destroyed, that technological superstructure could not easily be rebuilt, because the resources used to build it the first time would no longer be at hand.

Ehrlich concluded: "If there is a full-scale nuclear war, odds are you can kiss the Northern Hemisphere goodbye. . . . Odds are also that the effects will be catastrophic in the Southern Hemisphere." If so, he declared, the scientists had decided for the first time that they "could not preclude the extinction of *Homo sapiens*." Small isolated human groups might persist for several generations in a strange, inhospitable environment in the Southern Hemisphere, their adaptive capacities sapped by inbreeding and a burden of genetic defects from the postwar exposure to ionizing radiation and increased ultraviolet-B—a classic recipe for extinction.

Where can we go from here?

Clearly, society can never again view the prospect of nuclear war as it did before. Any possibility of meaningful survival has been removed, and no place on Earth is safe from the nuclear winter. But these newly discovered consequences of nuclear war are so all-encompassing and so devastating that most people need some time to absorb the implications. The question, therefore, is how soon a realization of the significance of these findings can be translated into a concerted, worldwide effort to reduce international tensions.

Critics of the conference and its conclusions have contended that release of the findings was premature and would frighten an already frightened public. In fact, the findings were held in confidence until they had been carefully reviewed by dozens of competent specialists and even confirmed in other studies.

The public no doubt will be frightened. But in recent years the details of the *known* consequences have repeatedly been underplayed by government representatives and largely ignored by the media and educational authorities. The pervasive feeling among the American public seems to have been that it would never happen or, if it did, it would be terrible, but many would survive and civilization would soon be rebuilt.

The latter myth has now been given the lie, in no uncertain terms. Far worse than merely ruining the economies of the superpowers and their allies—as was the case in Europe and Japan following World War II—nuclear war could render all but uninhabitable the only known habitable planet in the universe. Nothing of value to anyone alive today is likely to survive such a catastrophe—and least of all, the ideologies that supposedly motivated it. The virtues of freedom—or communism—pale when survival is not an available option and there may be no future generations to whom it can be bequeathed.

Advocates of deterrence would have us believe that these findings confirm its value. After all, a nuclear war hasn't happened yet, and the newly perceived consequences only make it that much more unthinkable. Deterrence, therefore, will be more effective than ever.

This view, however, allows for no mistakes, no human or computer error. Yet over the past few years there have been hundreds of computer errors, telling the United States that attack was imminent; no doubt similar errors have been made by less sophisticated Soviet computers. Six months ago human military minds misjudged the intentions of a Korean Airline pilot and killed over 200 civilians—hardly enhancing the credibility of deterrence.

Can the world risk *everything* on the shaky hopes based on deterrence? Even now the Soviets may be moving toward "launch on warning," and tensions between the two superpowers have never been higher. The public—including citizens of every nation on Earth—indeed has reason to be frightened and the right to demand a complete change in policy. □

1. S. Borgstrom and others, "Effects of a Nuclear War on Health and Health Services," World Health Organization, *Publication A36.12* (1983).
2. Carl Sagan, "Nuclear War and Climatic Catastrophe: Some Implications," *Foreign Affairs* 62 (Winter 1983), pp. 257–92.
3. C. Covey, S.H. Schneider, and S.L. Thompson, "Global Atmospheric Effects of Massive Smoke Injection from a Nuclear War: Results form General Circulation Model Simulations," *Nature* (submitted); V.V. Aleksandrov and G.L. Stenchikov, "On the Modeling of the Climatic Consequences of the Nuclear War," USSR Academy of Sciences, Computing Center, The Proceedings on Applied Mathematics (Moscow: 1983); J. Knox, *Report UCRL-89907,* Lawrence Livermore Laboratory (1983).
4. P.R. and A.H. Ehrlich, *Extinction: The Causes and Consequences of the Disappearance of Species* (New York: Random House, 1981).

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