EFFECTS

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This is an edited extract from The Cold and the Dark: the World After Nuclear War, by Paul Ehrlich, Carl Sagan, Donald Kennedy and Walter Orr Roberts, to be published on August 23 by Sidgwick and Jackson at £8.95. The book is based on the conference on the long-term, world-wide biological consequences of nuclear war, which opened in Washington on October 31, 1983. First reports of the conference appeared in Futures ("After the Ball is Over," by Norman Myers) on November 3, 1983. Two lengthy papers outlining the thesis of the nuclear winter and the biological consequences of nuclear war were subsequently published in the US magazine Science on December 23, 1983.

Frozen in the heat of battle

Carl Sagan

WE stumbled upon the "nuclear winter" by accident, by a circuitous route, by one of those circumstances common in science where studying something purely for its intellectual interest leads you to conclusions of surprising practical utility. For me, it began in 1971 with the Mariner 9 exploration of the planet Mars. Mariner 9 was the first spacecraft to orbit another planet. It arrived at Mars to find the planet completely covered with a global dust storm.

During the first three months, there was very little to look at except the dust in the atmosphere. There was an instrument on board the spacecraft called an infrared interferometric spectrometer, which had the ability to examine the atmosphere at various wavelengths and therefore to probe to different depths in the atmosphere — from very high altitudes down to the surface.

We were able to see the temperature of the atmosphere and that of the surface change with time. The results showed that the atmosphere was considerably warmer than is usually the case on Mars, and the surface considerably colder. As the dust settled out, the atmosphere became cooler and the surface warmer — both approaching their usual, or "ambient," values.

It was not difficult to understand the reasons for this. The winds had stirred a great deal of dust off the Martian deserts into the atmosphere. Sunlight was being absorbed by the high altitude dust, thereby heating the atmosphere. But, by the same token, the sunlight was impeded from reaching the surface, and so the surface was cooled. An observer on Mars would have noticed, after the dust storm stirred, that cold and darkness were spreading over the planet.

Such dust storms are a Martian commonplace, and have been noted by ground-based observers for more than a century. They characteristically arise in the same few locations on Mars, spread first in longitude, then in latitude, and in a matter of a few weeks at most typically cross the Martian equator into the other hemisphere. Now, the surface atmospheric pressure on Mars is about the same as that in the stratosphere of the Earth. Mars rotates, as the earth does, once every twenty-four hours, and its axis of rotation is tilted to its orbital plane by just about the same angle as the Earth's. There are differences between Mars and Earth, of course — including the absence of oceans on Mars, and the fact that it is farther away from the sun. But it seemed to us that the Martian experience might be relevant to Earth.

A number of us, having little before us for the first three months after orbital injection but the dust storm, set to calculating by how much the atmosphere should be warmed and the surface cooled for a given amount of dust put up into the atmosphere.

A rough calculation was not very difficult, and several different groups were able to understand not just qualitatively but quantitatively the temperature changes that the dust storm had brought temporarily to Mars. My colleagues (and former students) James B. Pollack and O. Brian Toon, both now at the NASA Ames Research Center, were eager to apply this kind of computational armamentarium to terrestrial problems.

We set out trying to understand what happens to the climate of the Earth when a large volcano goes off and distributes stratospheric aerosols worldwide. In some cases, we know how much dust is put into the upper atmosphere, what the particle sizes of the dust are, and what the composition of the fine particles is (generally sulphuric acid and silicates).

Because the stratosphere is very dry, rain does not carry these aerosols out; and because convection is very muted in the stratosphere, atmospheric motions tend not to carry the fine aerosols out. And so they slowly sink by their own weight — slowly because their sizes are so small — taking more than a year for the stratosphere to clear.

At the same time, there are, for many volcanic explosions, measurements of a small but definite global temperature decline — for all volcanic explosions in the last few centuries, a cooling of a degree or less. We found that we were able to calculate these temperature declines fairly accurately; the methods developed for Mars, and considerably extended since, worked quite well for Earth.

We had known, of course, that nuclear explosions put large amounts of fine dust into the atmosphere, and had talked on and off for a period of years about calculating what the climatic effects of this dust might be. At a meeting at Ames Research Center (devoted in part to the question of the origin of life) in 1981, we decided to go ahead with the calculations. The effort was further spurred a year later by word of some very interesting work performed by Paul Crutzen of the Max-Planck-Institute for Chemistry in Mainz and by John Birks of the University of Colorado. Crutzen and Birks had made a preliminary estimate of the amount of smoke from the burning of forests and cities that might be released into the atmosphere in a nuclear war. Clearly here was an additional important source of fine particles that might attenuate sunlight.

SO NOW I come to the question of the effects of nuclear war. By the usual accounting there are around 18,000 strategic and theatre thermonuclear weapons and the equivalent number of fission triggers in the American and Soviet strategic arsenals, with an aggregate yield of about 10,000 megatons. The total number of nuclear weapons (strategic plus theatre and tactical) in the arsenals of the two nations is close to 50,000, with an aggregate yield near 15,000 megatons.

No one knows, of course, how many warheads with what aggregate yield would be detonated in a nuclear war. On the other hand, it is generally accepted, even among most military planners, that a "small" nuclear war would be almost impossible to contain before it escalated to include much of the world arsenals.

For this reason alone, any serious attempt to examine the possible consequences of nuclear war must place major emphasis on large-scale exchanges in the 5,000 to 7,000-megaton range — between about a third and a half of the world strategic inventories — and many studies have done so. Many of the effects described below, however, can be triggered by much smaller wars.

The adversary's strat airfields, missile silos, n bases, submarines at weapons manufacturing storage locales, civilian military command and trol centres, attack as ment and early-warning fa lities, and the like are pr able targets ("counterfo attack"). While it is of stated that cities are targeted *per se*, many of t above targets are proxima to or collocated with citi especially in Europe. In ad tion, there is an industri targeting category ("count value attack").

Modern nuclear doctrin require that "war-supp ting" facilities be attack Many of these facilities necessarily industrial nature, and engage a wo force of considerable si They are almost always si ated near major transpor tion centres, so that r materials and finished pr ducts can be efficiently tra ported to other industri sectors, or to forces in t field. Thus, such faciliti are, almost by definitio cities, or near or within citi

Other "war-supportin targets may include the tra portation systems themselv (roads, canals, rivers, ra ways, civilian airfields, et petroleum refineries, stora sites and pipelines, hy roelectric and nuclear pow plants, radio and televisi transmitters, and the like. major countervalue exchan therefore might involv almost all large cities in t United States and the Sovi Union, and possibly most the large cities in the Nort ern Hemisphere. There a fewer than 2,500 cities in t world with populations over 100,000 inhabitants, the devastation of all su cities is well within the mea of the world nuclear arsena

Recent estimates of t immediate deaths from blas prompt radiation, and fires a major exchange in whic cities were targeted ran from several hundred millio to 1.1 billion people.

Serious injuries requiri immediate medical attenti (which would be large unavailable) would be su fered by a comparably lar number of people, perhaps a additional 1.1 billion. Thus is possible that somethi approaching half the huma population on the plan would be killed or serious injured by the direct effects a nuclear war. But a range additional effects — som unexpected, some inadeq ately treated in earlier st dies, some uncovered by only recently — makes th picture much more sombr still.

Destruction of missile silos command and control facil ties, and other hardened site requires nuclear weapons o fairly high yield exploded a ground bursts or as low ai bursts. High-yield groun bursts will vaporise, mel and pulverise the surface a the target area and prope large quantities of conden sates and fine dust into th

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upper troposphere and stratosphere.

The particles are chiefly entrained in the rising fireball; some ride up the stem of the mushroom cloud. Most military targets, however, are not very hard. The destruction of cities can be accomplished, as demonstrated at Hiroshima and Nagasaki, by lower-yield explosions less than a kilometre above the surface. Low-yield air bursts over cities or near forests will tend to produce massive fires, in some cases over a total area of 100,000 square kilometres or more. City fires generate enormous quantities of black smoke which rise at least into the upper part of the lower atmosphere, or troposphere. If firestorms occur, the smoke column rises vigorously, like the draught in a fireplace, and may (the question is still unresolved) carry some of the soot into the lower part of the upper atmosphere, or stratosphere. The smoke from forest and grassland fires would initially be restricted to the lower troposphere.

The fission of the (generally plutonium) trigger in every thermonuclear weapon and the reactions in the (generally uranium-238) casing added as a fission yield "booster" produce a witch's brew of radioactive products, which are also entrained in the cloud. Each such product, or radioisotope, has a characteristic half-life (defined as the time to decay to half of its original level of radioactivity). Most of the radioisotopes have very short half-lives, and decay in hours to days.

Particles injected into the stratosphere, mainly by high-yield explosions, fall out very slowly — characteristically in about a year, by which time most of the fission products, even when concentrated, will have decayed to much safer levels. Particles injected into the troposphere by low-yield explosions and fires fall out more rapidly — by coagulation, gravitational settling, rainout, convection, and other processes — before the radioactivity has decayed to moderately safe levels. Thus, rapid fallout of tropospheric radioactive debris tends to produce larger doses of ionizing radiation than does the slower fallout of radioactive particles from the stratosphere.

Nuclear explosions of more than one megaton yield generate a radiant fireball that rises through the troposphere fully into the stratosphere. The fireballs from weapons with yields between 100 and 1,000 kilotons (1,000 kilotons = 1 megaton) will partially extend into the stratosphere. The high temperatures in the fireball chemically ignite some of the nitrogen in the air, producing oxides of nitrogen, which in turn chemically attack and destroy the gas ozone in the middle stratosphere. But ozone absorbs the biologically dangerous ultraviolet radiation from the sun. Thus, the partial depletion of the stratospheric ozone layer, or "ozonosphere," by high-yield nuclear explosions will ultraviolet radiation at the surface of the Earth (after the soot and dust have settled out).

After a nuclear war in which thousands of high-yield weapons are detonated, the increase in biologically dangerous ultraviolet light might be several hundred per cent. In the more dangerous shorter wavelengths, larger increases would occur. Nucleic acids and proteins, the fundamental molecules for life on Earth, are especially sensitive to ultraviolet radiation. Thus, an increase in the solar ultraviolet flux at the surface of the Earth is potentially dangerous to life.

These four effects — obscuring smoke in the troposphere, obscuring dust in the stratosphere, the fallout of radioactive debris, and the partial destruction of the ozone layer — constitute the four known principal adverse environmental consequences that would occur after a nuclear war is "over." There may well be others about which we are still ignorant. The dust and, especially, the dark soot absorb ordinary visible light from the sun, heating the atmosphere and cooling the Earth's surface.

All four of these effects have been treated in our recent study. For the first time it is demonstrated that severe and prolonged low temperatures, the "nuclear winter," would follow a nuclear war.

The new results have been subjected to detailed scrutiny, and many corroboratory calculations have now been made, including at least two in the Soviet Union.

Unlike many previous studies, the effects do not seem to be restricted to northern midlatitudes, where the nuclear exchange would mainly take place. There is now substantial evidence that the heating by sunlight of atmospheric dust and soot over northern midlatitude targets would profoundly change the global circulation. Fine particles would be transported across the equator in weeks, as is the case on Mars, bringing the cold and the dark to the southern hemisphere. While it would be less cold and less dark at the ground in the southern hemisphere than in the northern, massive climatic and environmental disruptions may be triggered there as well.

Predicted continental temperatures in the northern hemisphere vary after nuclear war — to as low as — 50° F. The high heat capacity of water guarantees that ocean temperatures will fall at most by a few degrees. Because temperatures are moderated by the adjacent oceans, temperatures in coastal regions will be less extreme than in continental interiors. However, the very sharp temperature contrast between the frozen continents and the only slightly cooled oceans will produce continuing storms of unprecedented severity along coastlines, and the preferential rainout and washout of radioactivity there indicate that neither continental interiors nor coastlines will be spared.

Because of the obscuration of the sun, the daytime light gloom or worse. For more than a week in the northern midlatitude target zone, it might be much too dark to see, even at midday.

Perhaps the most striking and unexpected consequence of our study is that even a comparatively small nuclear war can have devastating climatic consequences, provided cities are targeted. There is an indication of a very approximate threshold at which severe climatic consequences are triggered — by 100 or more nuclear explosions over cities, for smoke generation, or around 2,000 to 3,000 high-yield surface and low air bursts at, for example, missile silos, for dust generation and ancillary fires. Fine particles can be injected into the atmosphere at increasing rates with only minor effects until these thresholds are crossed. Thereafter, the effects increase rapidly in severity.

These calculations are not, and cannot be, assured prognostications of the full consequences of a nuclear war. Many refinements in them are possible and are being pursued. But there seems to be general agreement on the overall conclusions: in the wake of a nuclear war there is likely to be a period, lasting at least for months, of extreme cold in a radioactive gloom, followed — after the soot and dust falls out — by an extended period of increased ultraviolet light reaching the surface.

THERE HAS been a systematic tendency for the effects of nuclear weapons and nuclear war to be underestimated. The yield of the first nuclear explosion near Alamogordo, New Mexico, on July 16, 1945, was underestimated by almost all those who designed and constructed the weapon. The extent of fallout from early thermonuclear weapons tests was underestimated; the impairment or destruction of satellites by nuclear weapons explosions in space was a surprise; the depletion of the ozonosphere by high-yield bursts was unanticipated; and nuclear winter was for many — ourselves included — an astonishment. What else have we overlooked?

One, possibly serious, additional effect is the production of toxic gases by city fires. It is now a commonplace that in the burning of modern tall buildings, more people succumb to toxic gases than to fire. Ignition of many varieties of building materials, insulation, and fabrics generates large amounts of such pyrotoxins, including carbon monoxide, cyanides, vinyl chloride, oxides of nitrogen, ozone, dioxins, and furans. Because of differing practices in the use of such synthetics, the burning of cities in North America and Western Europe would probably generate more pyrotoxins than cities in the Soviet Union, and cities with substantial recent construction more than older unreconstructed cities. In nuclear war scenarios in which a great many cities are burning, a significant pyrotoxin smog might persist for months. The magnitude of this danger is unknown.

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*Professor Carl Sagan
director of the Laboratory
Planetary Studies at Corn
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