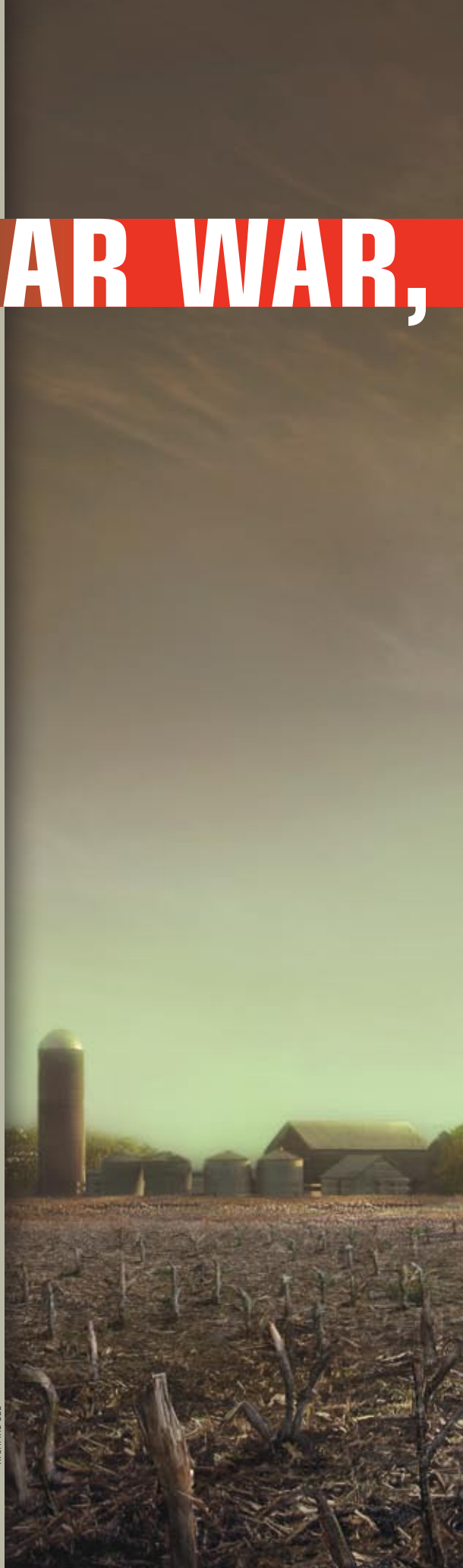
LOCAL NUCLEAR WAR,

Worry has focused on the U.S. versus Russia, but a regional nuclear war between India and Pakistan could blot out the sun, starving much of the human race

BY ALAN ROBOCK AND OWEN BRIAN TOON



RICHARD LEE

KEY CONCEPTS

- Nuclear bombs dropped on cities and industrial areas in a fight between India and Pakistan would start firestorms that would put massive amounts of smoke into the upper atmosphere.
- The particles would remain there for years, blocking the sun, making the earth's surface cold, dark and dry. Agricultural collapse and mass starvation could follow. Hence, global cooling could result from a regional war, not just a conflict between the U.S. and Russia.
- Cooling scenarios are based on computer models. But observations of volcanic eruptions, forest fire smoke and other phenomena provide confidence that the models are correct.

—The Editors

Twenty-five years ago international teams of scientists showed that a nuclear war between the U.S. and the Soviet Union could produce a "nuclear winter." The smoke from vast fires started by bombs dropped on cities and industrial areas would envelop the planet and absorb so much sunlight that the earth's surface would get cold, dark and dry, killing plants worldwide and eliminating our food supply. Surface temperatures would reach winter values in the summer. International discussion about this prediction, fueled largely by astronomer Carl Sagan, forced the leaders of the two superpowers to confront the possibility that their arms race endangered not just themselves but the entire human race. Countries large and small demanded disarmament.

Nuclear winter became an important factor in ending the nuclear arms race. Looking back later, in 2000, former Soviet Union leader Mikhail S. Gorbachev observed, "Models made by Russian and American scientists showed that a nuclear war would result in a nuclear winter that would be extremely destructive to all life on earth; the knowledge of that was a great stimulus to us, to people of honor and morality, to act."

Why discuss this topic now that the cold war has ended? Because as other nations continue to acquire nuclear weapons, smaller, regional nuclear wars could create a similar global catastrophe. New analyses reveal that a conflict between India and Pakistan, for example, in which

GLOBAL SUFFERING

HUMAN TOLL

An all-out nuclear war between India and Pakistan could slaughter people locally and lead to more deaths across the planet.

20 million people in the region could die from direct bomb blasts and subsequent fire and radiation.

1 billion people worldwide with marginal food supplies today could die of starvation because of ensuing agricultural collapse.

100 nuclear bombs were dropped on cities and industrial areas—only 0.4 percent of the world's more than 25,000 warheads—would produce enough smoke to cripple global agriculture. A regional war could cause widespread loss of life even in countries far away from the conflict.

Regional War Threatens the World

By deploying modern computers and modern climate models, the two of us and our colleagues have shown that not only were the ideas of the 1980s correct but the effects would last for at least 10 years, much longer than previously thought. And by doing calculations that assess decades of time, only now possible with fast, current computers, and by including in our calculations the oceans and the entire atmosphere—also only now possible—we have found that the smoke from even a regional war would be heated and lofted by the sun and remain suspended in the upper atmosphere for years, continuing to block sunlight and to cool the earth.

India and Pakistan, which together have more than 100 nuclear weapons, may be the most worrisome adversaries capable of a regional nuclear conflict today. But other countries besides the U.S. and Russia (which have thousands) are well endowed: China, France and the U.K. have hundreds of nuclear warheads; Israel has more than 80, North Korea has about 10 and Iran may well be trying to make its own. In 2004 this situation prompted one of us (Toon) and later Rich Turco of the University of California, Los Angeles, both veterans of the 1980s investigations, to begin evaluating what the global environmental effects of a regional nuclear war would be and to take as our test case an engagement between India and Pakistan.

The latest estimates by David Albright of the Institute for Science and International Security and by Robert S. Norris of the Natural Resources Defense Council are that India has 50 to 60 assembled weapons (with enough plutonium for 100) and that Pakistan has 60 weapons. Both countries continue to increase their arsenals. Indian and Pakistani nuclear weapons tests indicate that the yield of the warheads would be similar to the 15-kiloton explosive yield (equivalent to 15,000 tons of TNT) of the bomb the U.S. used on Hiroshima.

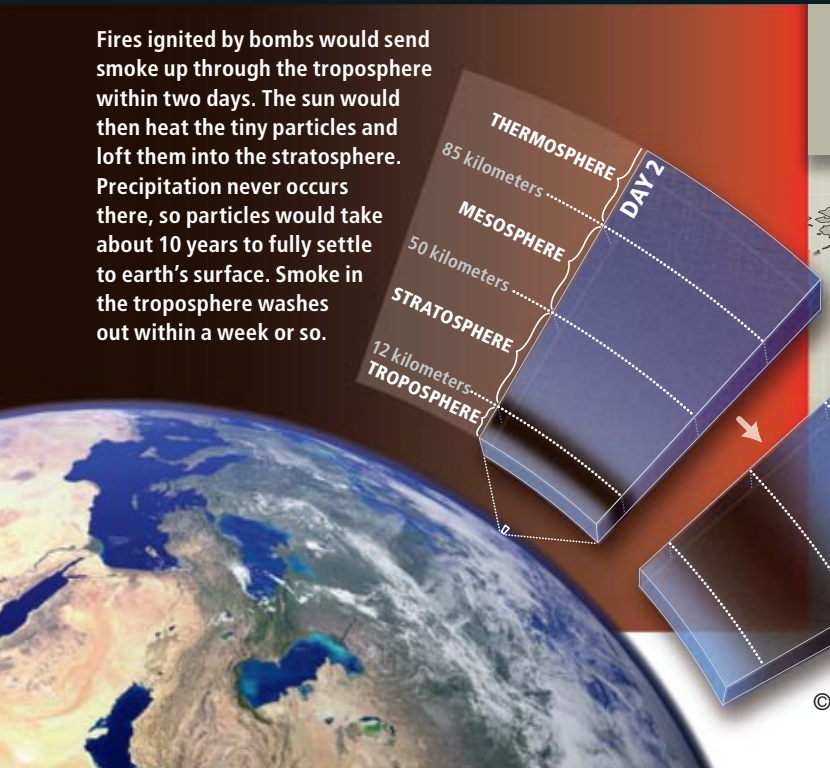
Toon and Turco, along with Charles Bardeen, now at the National Center for Atmospheric Research, modeled what would happen if 50 Hiroshima-size bombs were dropped across the highest population-density targets in Pakistan and if 50 similar bombs were also dropped across India. Some people maintain that nuclear weapons would be used in only a measured way. But in the wake of chaos, fear and broken communications that would occur once a nuclear war began, we doubt leaders would limit attacks in any rational manner. This likelihood is particularly true for Pakistan, which is small and could be quickly overrun in a conventional conflict. Peter R. La-

NASA/THE VISIBLE EARTH (*globe*); JEN CHRISTIANSEN (*atmosphere cutaway and smoke-density maps*)

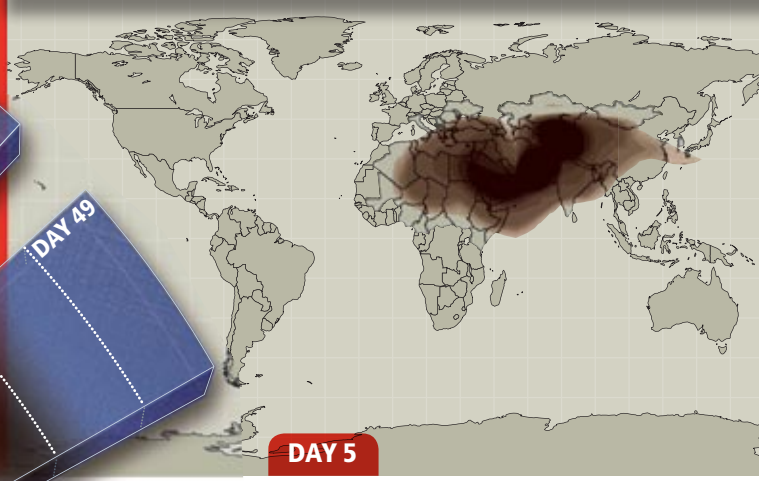
[ATMOSPHERIC CHANGE]

SMOKE CLOAKS THE EARTH, BLOCKING THE SUN

Fires ignited by bombs would send smoke up through the troposphere within two days. The sun would then heat the tiny particles and loft them into the stratosphere. Precipitation never occurs there, so particles would take about 10 years to fully settle to earth's surface. Smoke in the troposphere washes out within a week or so.

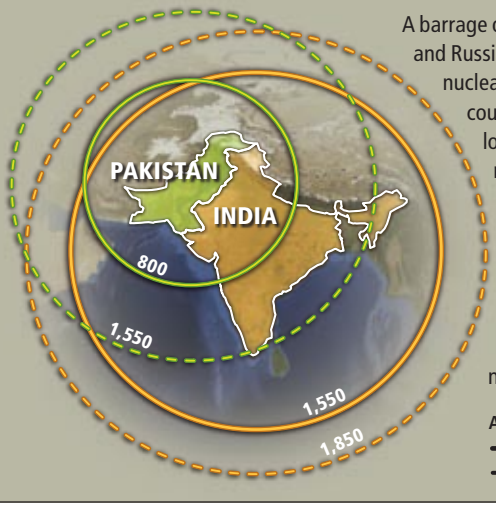


Fires resulting from 100 warheads detonated by India and Pakistan would generate at least five teragrams of smoke. Simulating weather patterns for an average May 15, the authors showed that heavy smoke would cover the



[NUCLEAR THREAT]

INDIA VS. PAKISTAN



A barrage of nuclear attacks between the U.S. and Russia could plunge the earth into nuclear winter, but regional conflicts could do the same. India and Pakistan, long at odds, have more than 50 nuclear warheads apiece; if each country dropped that many bombs on cities and industrial areas, the smoke from fires would stunt agriculture worldwide for 10 years. Ballistic missiles from either country could reach most if not all areas in the other's territory.

Approximate missile range (in miles)
— Operational range
– – In development

Globally, nine nations have nuclear weapons. By using their arsenals, all of the countries other than North Korea and Iran could jeopardize civilization.

COUNTRY	WARHEADS
Russia	15,000
U.S.	9,900
France	350
China	200
U.K.	200
Israel	80
Pakistan	60
India	50
North Korea	<10
Iran	In development?

SOURCE: Natural Resources Defense Council

JEN CHRISTIANSEN (*missile range map*); NASA/THE VISIBLE EARTH (*base map*); CATHERINE WILSON (*flags*)

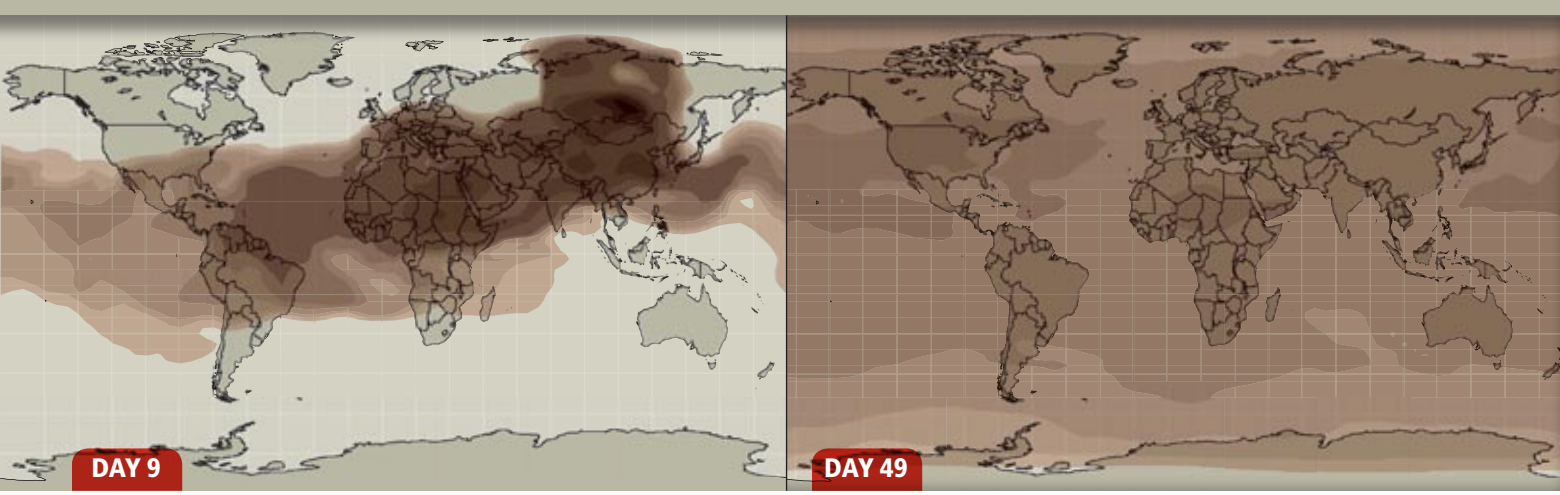
voy of the Naval Postgraduate School, for example, has analyzed the ways in which a conflict between India and Pakistan might occur and argues that Pakistan could face a decision to use all its nuclear arsenal quickly before India swamps its military bases with traditional forces.

Obviously, we hope the number of nuclear targets in any future war will be zero, but policy makers and voters should know what is possible. Toon and Turco found that more than 20 million people in the two countries could die from the blasts, fires and radioactivity—a horrible slaughter. But the investigators were shocked to discover that a tremendous amount of smoke would be generated, given the megacities in the two countries, assuming each fire would burn the same area that actually did burn in Hiroshima and assuming an amount of burnable material per person based on various studies. They calculated that the 50 bombs exploded in Pakistan would produce three teragrams of smoke, and the 50 bombs hitting India would generate four (one teragram equals a million metric tons).

Satellite observations of actual forest fires have shown that smoke can be lofted up through the troposphere (the bottom layer of the atmosphere)

Pakistan could elect to use its nuclear arsenal before India swamps its military bases.

region after five days. Within nine days the soot would extend around the globe. After 49 days the particles would blanket the inhabited earth, blocking enough sunlight that skies would look overcast perpetually, everywhere.



WHY BELIEVE IT

Some people think that the nuclear winter theory developed in the 1980s was discredited. And they may therefore raise their eyebrows at our new assertion that a regional nuclear war, like one between India and Pakistan, could also devastate agriculture worldwide. But the original theory was thoroughly validated. The science behind it was supported by investigations from the National Academy of Sciences, by studies sponsored within the U.S. military, and by the International Council of Scientific Unions, which included representatives from 74 national academies of science and other scientific bodies.

Our current work has appeared in leading peer-reviewed journals. Still, we seem to be the only ones pursuing research into the global environmental risks of nuclear exchanges. We urge others to evaluate and repeat the calculations both for the effects of a superpower conflagration and for more regional nuclear wars. ***—A.R. and O.B.T.***

[THE AUTHORS]

Alan Robock is professor of climatology at Rutgers University and associate director of the school's Center for Environmental Prediction, where he studies many aspects of climate change. He is a fellow of the American Meteorological Society and a participant in the Intergovernmental Panel on Climate Change. Owen Brian Toon is chair of the department of atmospheric and oceanic sciences at the University of Colorado at Boulder and a fellow of the Laboratory for Atmospheric and Space Physics there. He is a fellow of the American Meteorological Society and the American Geophysical Union.

and sometimes then into the lower stratosphere (the layer just above, extending to about 30 miles). Toon and Turco also did some "back of the envelope" calculations of the possible climate impact of the smoke should it enter the stratosphere. The large magnitude of such effects made them realize they needed help from a climate modeler.

It turned out that one of us (Robock) was already working with Luke Oman, now at the NASA Goddard Space Flight Center, who was finishing his Ph.D. at Rutgers University on the climatic effects of volcanic eruptions, and with Georgiy L. Stenchikov, also at Rutgers and an author of the first Russian work on nuclear winter. They developed a climate model that could be used fairly easily for the nuclear blast calculations.

Robock and his colleagues, being conservative, put five teragrams of smoke into their modeled upper troposphere over India and Pakistan on an imaginary May 15. The model calculated how winds would blow the smoke around the world and how the smoke particles would settle out from the atmosphere. The smoke covered all the continents within two weeks. The black, sooty smoke absorbed sunlight, warmed and rose into the stratosphere. Rain never falls there, so the air is never cleansed by precipitation; particles very slowly settle out by falling, with air resisting them. Soot particles are small, with an average diameter of only 0.1 micron (μm), and so drift down very slowly. They also rise during the daytime as they are heated by the sun, repeatedly delaying their elimination. The calculations showed that the smoke would reach far higher into the upper stratosphere than the sulfate particles that are produced by episodic volcanic eruptions. Sulfate particles are transparent and absorb much less sunlight than soot and are also bigger, typically 0.5 μm. The volcanic particles remain airborne for about two years, but smoke from nuclear fires would last a decade.

Killing Frosts in Summer

The climatic response to the smoke was surprising. Sunlight was immediately reduced, cooling the planet to temperatures lower than any experienced for the past 1,000 years. The global average cooling, of about 1.25 degrees Celsius (2.3 degrees Fahrenheit), lasted for several years, and even after 10 years the temperature was still 0.5 degree C colder than normal. The models also showed a 10 percent reduction in precipitation worldwide. Precipitation, river flow and soil moisture all decreased because blocking sunlight reduces evaporation and weakens the hydrologic cycle. Drought was largely concentrated in the lower latitudes, however, because global cooling would retard the Hadley air circulation pattern in the tropics, which produces a large fraction of global precipitation. In critical areas such as the Asian monsoon regions, rainfall dropped by as much as 40 percent.

The cooling might not seem like much, but even a small dip can cause severe consequences. Cooling and diminished sunlight would, for example, shorten growing seasons in the midlatitudes. More insight into the effects of cooling came from analyses of the aftermaths of massive volcanic eruptions. Every once in a while such eruptions produce temporary cooling for a year or two. The largest of the past 500 years, the 1815 Tambora eruption in Indonesia, blotted the sun and produced global cooling of about 0.5 degree C for a year; 1816 became known as "The Year without a Summer" or "Eighteen Hundred and Froze to Death." In New England, although the average summer temperature was lowered only a few degrees, crop-killing frosts occurred in every month. After the first frost, farmers replanted crops, only to see them killed by the next frost. The price of grain skyrocketed, the price of livestock plummeted as farmers sold the animals they could not feed, and a mass migration began from New England to the Midwest, as people followed reports of fertile land there. In Europe the weather was so cold and gloomy that the stock market collapsed, widespread famines occurred and 18-year-old Mary Shelley was inspired to write *Frankenstein*.

Certain strains of crops, such as winter wheat, can withstand lower temperatures, but a lack of sunlight inhibits their ability to grow. In our scenario, daylight would filter through the high smoky haze, but on the ground every day would seem to be fully overcast. Agronomists and farmers could not develop the necessary seeds or adjust agricultural practices for the radically different conditions unless they knew ahead of time what to expect.

In addition to the cooling, drying and darkness, extensive ozone depletion would result as the smoke heated the stratosphere; reactions that create and destroy ozone are temperature-dependent. Michael J. Mills of the University of Colorado at Boulder ran a completely separate climate model from Robock's but found similar results for smoke lofting and stratospheric temperature changes. He concluded that although surface temperatures would cool by a small amount, the

COURTESY OF SHERRI L. WEST (*Robock*); COURTESY OF OWEN BRIAN TOON (*Toon*)

stratosphere would be heated by more than 50 degrees C, because the black smoke particles absorb sunlight. This heating, in turn, would modify winds in the stratosphere, which would carry ozone-destroying nitrogen oxides into its upper reaches. Together the high temperatures and nitrogen oxides would reduce ozone to the same dangerous levels we now experience below the ozone hole above Antarctica every spring. Ultraviolet radiation on the ground would increase significantly because of the diminished ozone.

Less sunlight and precipitation, cold spells, shorter growing seasons and more ultraviolet radiation would all reduce or eliminate agricultural production. Notably, cooling and ozone loss would be most profound in middle and high latitudes in both hemispheres, whereas precipitation declines would be greatest in the tropics.

The specific damage inflicted by each of these environmental changes would depend on particular crops, soils, agricultural practices and regional weather patterns, and no researchers have completed detailed analyses of such agricultural responses. Even in normal times, however, feeding the growing human population depends on transferring food across the globe to make up for regional farming deficiencies caused by drought and seasonal weather changes. The total amount of grain stored on the planet today would feed the earth's population for only about two months [see "Could Food Shortages Bring Down Civilization?" by Lester R. Brown; Scientific American, May]. Most cities and countries have stockpiled food supplies for just a very short period, and food shortages (as well as rising prices) have increased in recent years. A nuclear war could trigger declines in yield nearly everywhere at once, and a worldwide panic could bring the global agricultural trading system to a halt, with severe shortages in many places. Around one billion people worldwide who now live on marginal food supplies would be directly threatened with starvation by a nuclear war between India and Pakistan or between other regional nuclear powers.

Independent Evidence Needed

Typically scientists test models and theories by doing experiments, but we obviously cannot experiment in this case. Thus, we look for analogues that can verify our models.

Burned cities. Unfortunately, firestorms created by intense releases of energy have pumped vast quantities of smoke into the upper atmosphere. San Francisco burned as a result of the 1906 earthquake, and whole cities were incin-

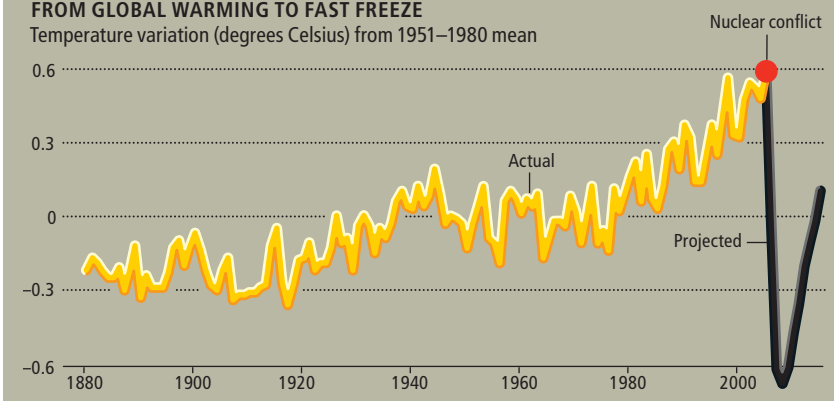
[ENVIRONMENTAL FALLOUT]

Agriculture Collapses

Five teragrams of smoke shrouding the earth would cause temperatures to drop and ultraviolet radiation to rise, threatening crops worldwide.

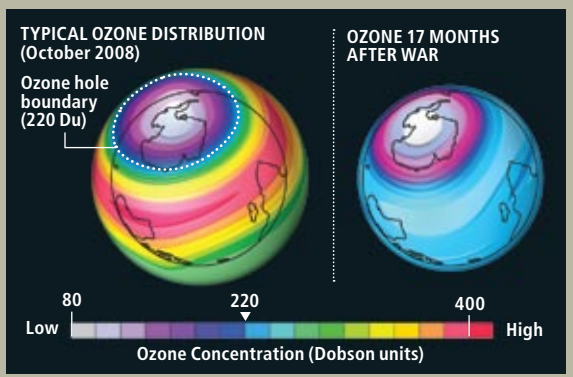
TEMPERATURE

The average surface-air temperature around the globe would drop by 1.25 degrees Celsius, and after 10 years would still be 0.5 degree lower. The depression would also trigger summer frosts.



OZONE DEPLETION

Smoke would absorb enough sunlight to greatly heat the stratosphere, drawing nitrogen oxides upward, thinning ozone concentration. In effect, the ozone hole that occurs annually over the South Pole (*left, purple* and *dark blue*) would exist globally (*right*), allowing dangerous levels of ultraviolet radiation to strike the earth's surface.



CROPS RUINED

Diminished sunlight, cooler temperatures and drought would shorten growing seasons. Unseasonal frosts and more ultraviolet radiation piercing through a thinner ozone layer would further harm crops. Yields would decline around the world all at once, halting food trade. Above, a severe cold snap in 2007 damaged 70 percent of California's citrus harvest.

CATHERINE WILSON (*graph*); SOURCE FOR GRAPH: "A CLOSER LOOK AT UNITED STATES AND GLOBAL SURFACE TEMPERATURE CHANGE," BY J. E. HANSEN ET AL., IN *JOURNAL OF GEOPHYSICAL RESEARCH*, VOL. 106; 2001 (*actual temperature variation*); GEORGE RETSECK (*ozone globes*); JUSTIN SULLIVAN *Getty Images* (*oranges*)

REAL EVENTS such as explosive volcanic eruptions and massive wildfires help to verify simulations that predict the consequences of nuclear war. In 1991 the Mount Pinatubo volcano threw ash miles into the air (*top*), which subsequently formed distinct particle layers that circumnavigated the planet (*bottom*).

erated during World War II, including Dresden, Hamburg, Tokyo, Hiroshima and Nagasaki. These events confirm that smoke from intense urban fires rises into the upper atmosphere.

The seasonal cycle. In actual winter the climate is cooler because the days are shorter and sunlight is less intense; the simple change of seasons helps us quantify the effects of less solar radiation. Our climate models re-create the seasonal cycle well, confirming that they properly reflect changes in sunlight.

Eruptions. Explosive volcanic eruptions, such as those of Tambora in 1815, Krakatau in 1883 and Pinatubo in 1991 provide several lessons. The resulting sulfate aerosol clouds that formed in the stratosphere were transported around the world by winds. The surface temperature plummeted after each eruption in proportion to the thickness of the particulate cloud. After the Pinatubo eruption, the global average surface temperature dropped by about 0.25 degree C. Global precipitation, river flow and soil moisture all decreased. Our models reproduce these effects.

Forest fires. Smoke from large forest fires sometimes is injected into the troposphere and lower stratosphere and is transported great distances, producing cooling. Our models perform well against these effects, too.

Extinction of the dinosaurs. An asteroid smashed into Mexico's Yucatán Peninsula 65 million years ago. The resulting dust cloud, mixed with smoke from fires, blocked the Sun, killing the dinosaurs. Massive volcanism in India at the same time may have exacerbated the effects. The events teach us that large amounts of aerosols in the earth's atmosphere can change climate drastically enough to kill robust species.

We have used such analogues to test and improve our models in the past. But we hope more people will do further work. Independent models that either verify or contradict ours would be very instructive. Agricultural impact studies, which we have not conducted, would be particularly welcomed.

Abolition: The Only Policy

People have several incorrect impressions about nuclear winter. One is that the climatic effects were disproved; this is just not true [*see sidebar on page 78*]. Another is that the world would experience "nuclear autumn" instead of winter. But our new calculations show that the climate effects even of a regional conflict would be widespread and severe. The models and computers used in the 1980s were not able to simulate the lofting and persistence of the smoke or the long time it would take oceans to warm back up as the smoke eventually dissipated; current models of a full-scale nuclear exchange predict a nuclear winter, not a nuclear fall.

Another misimpression is that the problem, even if it existed, has been solved by the end of the nuclear arms race. In fact, a nuclear winter could readily be produced by the American and Russian nuclear arsenals that are slated to remain in 2012. Furthermore, the increasing number of nuclear states raises the chances of a war starting deliberately or by accident. For example, North Korea has threatened war should the world stop its ships and inspect them for transporting nuclear materials. Fortunately, North Korea does not now have a usable nuclear arsenal, but it may have one capable of global reach in the near future. Some extremist leaders in India advocated attacking Pakistan with nuclear weapons following recent terrorist attacks on India. Because India could rapidly overrun Paki-

stan with conventional forces, it would be conceivable for Pakistan to attack India with nuclear weapons if it thought that India was about to go on the offensive. Iran has threatened to destroy Israel, already a nuclear power, which in turn has vowed never to allow Iran to become a nuclear state. Each of these examples represent countries that imagine their existence to be threatened completely and with little warning. These points of conflict have the potential to erupt suddenly.

The first nuclear war so shocked the world that in spite of the massive buildup of these weapons since then, they have never been used again. But the only way to eliminate the possibility of climatic catastrophe is to eliminate the weapons. Rapid reduction of the American and Russian arsenals would set an example for the rest of the world that nuclear weapons cannot be used and are not needed.

Under the Strategic Offensive Reductions Treaty, the U.S. and Russia both committed to reduce deployed strategic nuclear warheads down to between 1,700 to 2,200 apiece by the end of 2012. In July 2009 President Barack Obama and Russian president Dmitry Medvedev agreed to drop that range further, to 1,500 to 1,675 by 2016. Although smaller strategic arsenals are to be commended, our new results show that even the lower counts are far more than enough to destroy agriculture worldwide, as is a regional nuclear war. If this mother lode of weapons were used against urban targets, hundreds of millions of people would be killed and a whopping 180 Tg of smoke would be sent into the global stratosphere. Average temperatures would remain below freezing even in the summer for several years in major agricultural regions. Even the warheads on one missile-carrying submarine could produce enough smoke to create a global environmental disaster.

The combination of nuclear proliferation, political instability and urban demographics may constitute one of the greatest dangers to the stability of society since the dawn of humans. Only abolition of nuclear weapons will prevent a potential nightmare. Immediate reduction of U.S. and Russian arsenals to the same levels as other nuclear powers (a few hundred) would maintain their deterrence, reduce the possibility of nuclear winter and encourage the rest of the world to continue to work toward the goal of elimination.

President Obama understands this logic. In his first press conference as president, on February 9, 2009, he said, "It is important for the United States, in concert with Russia … to restart the conversations about how we can start reducing our nuclear arsenals in an effective way so that we then have the standing to go to other countries and start stitching back together the nonproliferation treaties." Then, on September 24, the president led the United Nations Security Council to approve a draft resolution that would step up efforts to rid the world of nuclear weapons. Our modeling results only strengthen the reasons to support further progress on such policy. ■

The only way to eliminate the possibility of climatic catastrophe is to eliminate the nuclear weapons.

CHARLES DHARAPAK *AP Photo*

PRESIDENT BARACK OBAMA and Russian president Dmitry Medvedev sign an agreement in July 2009 to reduce the number of each nation's deployed, strategic nuclear warheads. Further cuts could inspire all nuclear nations to dramatically reduce weapons worldwide.

MORE TO EXPLORE

Consequences of Regional-Scale Nuclear Conflicts. Owen B. Toon, Alan Robock, Richard P. Turco, Charles Bardeen, Luke Oman and Georgiy L. Stenchikov in *Science,* Vol. 315, pages 1224–1225; March 2, 2007.

Climatic Consequences of Regional Nuclear Conflicts. A. Robock, L. Oman, G. L. Stenchikov, O. B. Toon, C. Bardeen and R. P. Turco in *Atmospheric Chemistry and Physics,* Vol. 7, No. 8, pages 2003–2012; April 2007.

Nuclear Winter Revisited with a Modern Climate Model and Current Nuclear Arsenals: Still Catastrophic Consequences. Alan Robock, Luke Oman and Georgiy L. Stenchikov in *Journal of Geophysical Research,* Vol. 112; July 2007.

Massive Global Ozone Loss Predicted following Regional Nuclear Conflict. Michael J. Mills, Owen B. Toon, Richard P. Turco, Douglas E. Kinnison and Rolando R. Garcia in Proceedings of the *National Academy of Sciences USA,* Vol. 105, No. 14, pages 5307–5312; April 2008.

Environmental Consequences of Nuclear War. Owen B. Toon, Alan Robock and Richard P. Turco in *Physics Today,* Vol. 61, No. 12, pages 37–42; December 2008.