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Global Change and Future Earth

The Geoscience Perspective

Edited by **Tom Beer, Jianping Li and Keith Alverson**

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Global Change and Future Earth

Global Change and Future Earth is derived from the work of several programs of the International Union of Geodesy and Geophysics (IUGG). It demonstrates how multi- and interdisciplinary research outputs from the geoscience community can be applied to tackle the physical and societal impacts of climate change and contribute to the Future Earth program of the International Council for Science (now known as the International Science Council following a merger with the International Social Science Council). The volume brings together an international team of eminent researchers to provide authoritative reviews on the wide-ranging ramifications of climate change spanning eight key themes: planetary issues; geodetic issues; the Earth's fluid environment; regions of the Earth; urban environments; food security; risk, safety, and security; and climate change and global change. Covering the challenges faced by urban and rural areas, in both developed and developing countries, this volume provides an important resource for a global audience of graduate students and researchers from a broad range of disciplines, as well as policy advisers and practitioners.

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Global Change and Future Earth: The Geoscience Perspective

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Climatic Consequences and Agricultural Impacts of Nuclear Conflicts

Owen B. Toon, Alan Robock, Michael Mills, Lili Xia, and Charles Bardeen

Public debate about nuclear weapons is no longer common or sustained. It was barely a news story when Donald Trump, now president of the United States, argued during the presidential election that proliferation is bound to continue, and therefore the United States could save money by allowing Japan and South Korea to become nuclear states to counter North Korea (Sanger and Haberman, 2016). It was merely another daily story for President Trump to argue during the campaign that nuclear weapons should be considered for use against terrorist organizations such as ISIS, or in Europe because it has plenty of space (Sanger and Haberman, 2016). The U.S. population did not react when President Obama, who advocated the elimination of nuclear weapons, set in motion projects to upgrade weapons costing hundreds of billions of dollars in a time of financial constraint. Unfortunately, this lack of public interest or concern is not justified by the facts. We are only an accident, a mistake, or a deranged politician away from killing most of the world's population now. As arsenals and the number of nuclear weapons states continue to grow, the threat of a nuclear exchange is bound to grow in the future.

Nuclear-armed countries are a threat to people everywhere partly because of the destructive power of single weapons – one weapon is enough to destroy a small city – and partly because of the growing ability of nations to launch missiles across the globe. However, it is not just the brute force attack killing people in the geographically limited target zone that threatens people everywhere. Most people have forgotten nuclear winter. For example, Lepore (2017) states that "the nuclear-winter debate has long since been forgotten." However, she fails to cite any of the extensive scientific literature on this topic after about 1986. Of course, the debate is forgotten once the press decides not to report on the modern status of the debate. Many think that the theory was disproven, or that the end of the nuclear arms race and subsequent reduction of Russian and American nuclear arsenals eliminated the global dangers of nuclear war. But they are wrong.

Nuclear winter is an assault on the global climate system caused by smoke from fires ignited by the bombs. As the smoke rapidly spreads globally in the stratosphere it will reduce temperatures and rainfall, and destroy the global ozone layer, which shields us from harmful ultraviolet radiation from the Sun. Recently it has been shown that even the smoke created by the use of one hundred weapons of the size used on Hiroshima in the Second World War, comparable to the arsenals of India or Pakistan, could cause environmental damage that would extend globally, threatening the world food supply and creating mass starvation worldwide (Robock and Toon, 2012; Xia and Robock, 2013; Özdoğan et al., 2013; Mills et al., 2014; Xia et al., 2015). The effects of food loss would also be felt in the aggressor nation. Hence, being a nuclear aggressor is suicidal. The deaths from these environmental changes would likely be a factor of 10 or more larger than the direct casualties from the explosions – potentially threatening the bulk of the human population – and would not be limited to the combatants.

The Cold War nuclear standoff between the West and the East, which was based on mutual assured destruction (MAD), may be slowly evolving into a nuclear free-for-all (e.g., Evans, 2014). Former U.S. Secretaries of State George Shultz and Henry Kissinger, former U.S. Secretary of Defense William Perry and former U.S. Senator Sam Nunn founded the Nuclear Security Project, "an effort to galvanize global action to reduce urgent nuclear dangers and build support for reducing reliance on nuclear weapons, ultimately ending them as a threat to the world."[1] These warriors of the Cold War argue in a series of editorials in the *Wall Street Journal* (Shultz et al., 2007, 2008, 2010, 2011) that in a world with many nuclear powers, each capable of destroying any country on Earth, and terrorist groups with increasing potential to gain control of nuclear weapons, MAD no longer works and one can no longer assume that peace can be maintained through rational analysis, careful control of weapons or successful negotiation between well-defined states with clear national interests. The only solution, they argue, is to create a world without nuclear weapons.

The newer nuclear states such as India and Pakistan have nuclear arsenals at the levels of the Soviet Union and the Western powers in the early 1950s (Kristensen and Norris, 2013, 2014). If the weapons were used, they could destroy a large fraction of the infrastructure of any country on Earth. India, North Korea and Iran are developing ballistic weapons–delivery systems that can send nuclear warheads over intercontinental scales. In coming decades it is possible that there will be a global nuclear gridlock caused by multiple nuclear-armed Asian, American and European states each with differing goals and aspirations, and each with the capability to destroy any adversary purposefully and to destroy much of the rest of the world inadvertently.

Against this backdrop of expanding nuclear states, the concept of SAD, self-assured destruction, has been introduced (Robock and Toon, 2012). According to this concept it is suicidal to use nuclear weapons, even the not-so-modest arsenals of newer nuclear states such as Pakistan and India. Everyone recognizes that immense damage and loss of life will occur in the combatant countries as a result of the explosions of the weapons. However, it is not as well understood that worldwide environmental damage from even a regional conflict could be much worse than the direct effects of the explosions. The fires started from weapons exploding in cities will flood the upper atmosphere with smoke. Smoke absorbs sunlight, heating the upper atmosphere and destroying the protective ozone layer. The light-absorbing smoke also prevents sunlight from reaching the Earth's surface, driving global temperatures down enough to damage agriculture at mid-latitudes. The loss of agricultural productivity will create mass starvation globally, including in those countries that used the nuclear weapons. To reiterate, the deaths from these environmental changes would likely be a factor of 10 or more larger than the direct casualties from the explosions – potentially threatening the majority of the human population – and would not be limited to the combatants.

24.1 World Nuclear Arsenals

Figure 24.1 illustrates the history of the number of warheads on the planet, and those in Russia and the United States, which currently control more than 90% of the weapons (Kristensen and Norris, 2014). The world total peaked at around seventy thousand warheads in 1986, five years before the disintegration of the Soviet Union. The downward trend in nuclear weapons, begun in 1986, has continued to this day. However, most of the downward trend occurred in the 1990s, and the rate of decline has slowed. The 2016 world arsenal was near fifteen thousand weapons, about 22% of the peak in 1986. The Strategic Offensive Reductions Treaty (SORT) reached by Presidents George W. Bush and Vladimir Putin, and in place from 2003 to 2011, regulated the number of strategic warheads not to exceed seventeen hundred to twenty-two hundred for each country by 31 December 2012. The New Strategic Arms Reduction Treaty (New-START), developed under Presidents Barack Obama and Dmitry Medvedev and in place after 2011, results in similar numbers of deployed strategic warheads to those in the SORT treaty. Certain types of warheads were not counted in either the SORT or New START. Of the fifteen thousand total warheads believed to exist among all nuclear powers in 2016, only about thirty-seven

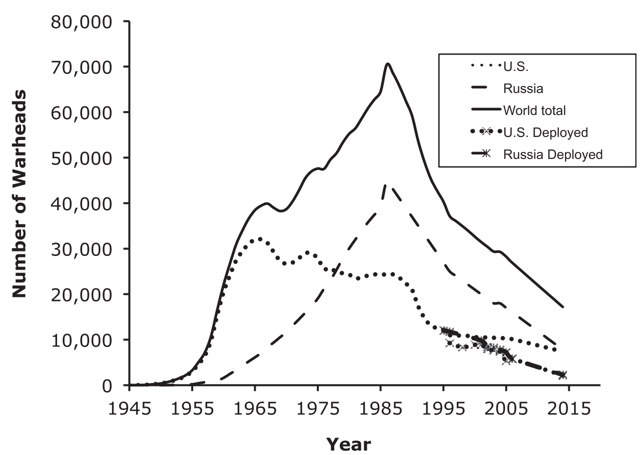

Figure 24.1 The number of nuclear warheads since World War II on the basis of data from Kristensen and Norris (2013) is shown. The arsenals of the United States, Russia and the world are depicted. After about 2000, Russia and the United States began to base treaties on the number of deployed strategic warheads, rather than the total number of warheads. Deployed strategic warheads are shown with symbols. In 2013, there were about 16,300 warheads in the world. About 6,200 of these were retired and ostensibly waiting to be destroyed. The United States and Russia had about 3,750 deployed strategic warheads, which are covered by treaties negotiated under the Bush and Obama administrations. Another 5,380 warheads were in storage, or considered not to be strategic, and therefore not covered in recent treaties (updated from box 2 in Toon et al., 2008).

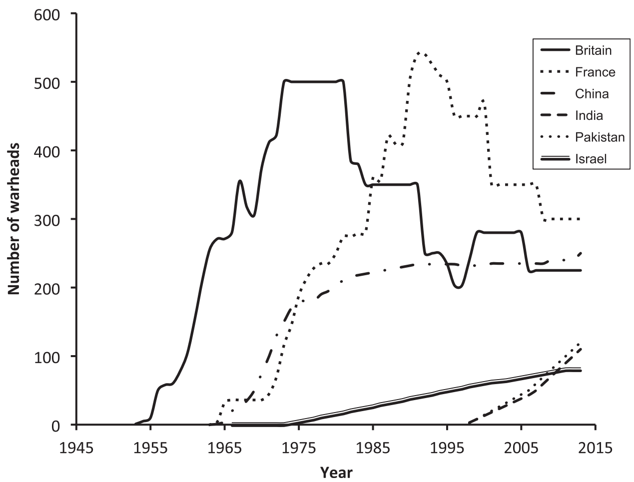

Figure 24.2 The number of warheads thought to be in the arsenals of Britain, France, China, India, Pakistan and Israel on the basis of data from Kristensen and Norris (2013) is illustrated. North Korean weapons are not shown because it is uncertain that they have an arsenal of usable weapons (from Toon et al., 2017).

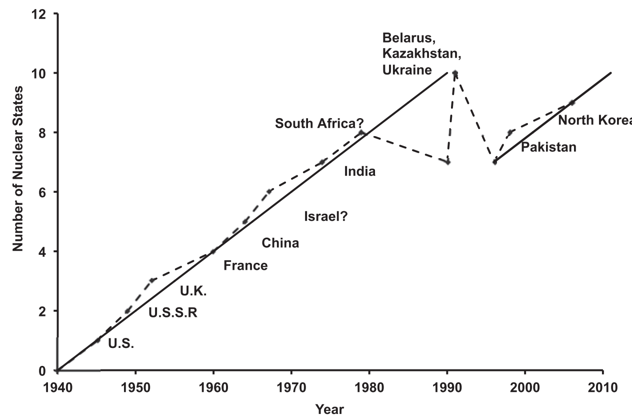

Figure 24.3 The dates when various nations obtained a nuclear warhead, mainly based on when they first tested a weapon, are shown. For Israel and South Africa the evidence for tests is controversial, so an estimate for when they had a usable weapon is given. Belarus, Kazakhstan and Ukraine inherited weapons from the Soviet Union and transferred them to Russia in the 1990s. South Africa gave up its weapons in the 1990s. The solid lines represent one new nuclear state every five years (updated from Box 2 in Toon et al., 2008).

hundred deployed strategic weapons are regulated under New START. About one thousand unregulated weapons are owned by France, China, the United Kingdom, Israel, Pakistan, India and North Korea together. Most of these weapons are not deployed, but are in storage. The remainder includes about seven thousand weapons in the United States and Russia that are considered either not deployed or not strategic (many are strategic warheads in storage; others are tactical weapons). There may be another five thousand warheads waiting to be dismantled in Russia and the United States. The United States also has twenty thousand plutonium pits in storage. Both Russia and the United States are embarked on expensive upgrades to their nuclear capabilities.

Figure 24.2 illustrates the arsenals of the countries with nuclear weapons other than the United States and Russia (Kristensen and Norris, 2013). It is very difficult to determine the numbers of weapons in most of these countries. While Britain and France have been slowly reducing their arsenals, and China seems to have maintained a constant level, Pakistan, India and possibly Israel seem to be increasing their arsenals. The yields of the weapons in most of the programs are not known. Britain, France and China have weapons with yields above one hundred kilotons (kt);[2] however, it is likely, on the basis of their nuclear tests, that India and Pakistan have weapons with yields similar to those of the U.S. weapons used in World War II, around ten to twenty kilotons, or even less.

Figure 24.3 outlines the history of nuclear proliferation. Up until the mid-1980s about one new nuclear state appeared every five years. Following the start of the build-down of nuclear weapons by the United States and Russia in 1986, a number of states abandoned their arsenals, or stopped nuclear weapons programs that were under consideration or development. South Africa developed a small nuclear arsenal and then abandoned it in the 1990s, the only country ever to abandon a self-developed nuclear arsenal. A number of countries inherited nuclear weapons from the former Soviet Union, but gave them up, including Kazakhstan, Belarus and Ukraine. Unfortunately, proliferation was renewed in 1998 when India and then Pakistan tested nuclear weapons. As Figure 24.3 indicates, the world now may be back on the trend of one new nuclear state about every five years.

Parts of the nuclear story are encouraging. Much of the world is ridding itself of nuclear weapons. Figure 24.4 shows the history of the development of nuclear-weapon-free zones. Almost one-third of the human population now lives in regions in which the United Nations has recognized treaties banning nuclear weapons. The Treaty for the Prohibition of Nuclear Weapons in Latin America and the Caribbean, also known as the Treaty of Tlatelolco, went into effect in 1968 and was eventually signed by all thirty-three independent nations of Latin America and the Caribbean, including Cuba. However, Brazil and Argentina reserved the right to conduct "peaceful nuclear weapons

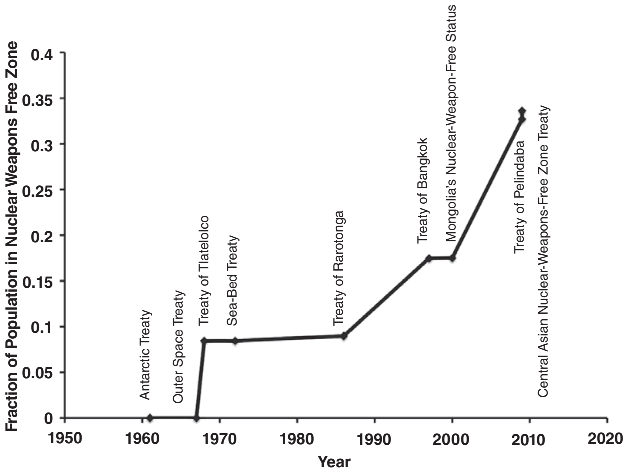

Figure 24.4 The fraction of the world's current population that lives in nuclear-weapon-free zones, as recognized through UN treaties, is shown. The names of the various treaties, as described in the text, are listed. Currently about one-third of Earth's population lives in a nuclear-free zone (from Toon et al., 2017).

explosions," and islands such as Puerto Rico, British Virgin Islands and Guadeloupe, associated with nuclear weapons states, are excluded. Africa established a nuclear-weapon-free zone under the Treaty of Pelindaba, which took effect in 2009. As a result of the additional treaties for Antarctica and the Rarotonga Treaty involving Australia, New Zealand and a number of island nations in the Pacific the entire Southern Hemisphere (with the exception of islands associated with states with nuclear weapons and international waters) is a nuclear-weapons-free zone. The Association of Southeast Asian Nations, including Brunei, Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam, became a nuclear-weapon free-zone in 1997 under the Bangkok Treaty. There is also a Central Asian nuclear free treaty signed by Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, which entered into force in 2009. Mongolia declared itself a nuclear-weapon-free zone in 1992, and it was formally recognized as such in 2012 by the five original nuclear weapons states: the United States, China, France, the United Kingdom and Russia. In total there are at least sixteen countries in Asia that are free of nuclear weapons, which is almost three times as many as Asian nuclear weapons states.

24.2 How Many Weapons Are Enough?

Comparison of Figure 24.1 and Figure 24.2 raises the question, How do you know how many weapons are enough? None of the nuclear weapons states has stated its criteria for answering this question.

In the case of the United States, analyses in the late 1940s reported by Eden (2004) identified militarily important industrial sites in the Soviet Union and concluded these could be destroyed by the delivery of one hundred atomic weapons, which were similar in yield to the weapons in the arsenals of present-day Pakistan, India and North Korea. Of course, weapons may not explode, or may never reach their target, so it was estimated that two hundred weapons would be needed for the United States to destroy the Soviet Union. Despite this estimate, the U.S. arsenal rose to more than 150 times this many weapons, and with typically more than ten times the average yield per weapon. One reason for the bloated number of weapons may be the competition between Russia and the United States and attempts by each to dominate the other so that a first strike might overwhelm the adversary (e.g., Lieber and Press, 2006). In the case of a first strike, each missile of the adversary must be targeted with multiple warheads. The opponent must then obtain even more warheads to be able to attack each of the enemy's missiles with more than one warhead. This competition to outnumber the other side leads to exponential growth in warheads. Alternative suggestions for the large numbers of weapons include competition for funding to support the nuclear infrastructure, political posturing, lack of planning or lack of thought about the size of the arsenal needed or concern that there would be a high failure rate of the weapons.

Toon et al. (2008) analyzed a modern attack on the urban areas in a number of countries. They found that in an attack on U.S. urban areas based on population density with one thousand weapons of one-hundred-kiloton yield, 48% of the U.S population would be within five kilometers of ground zero, 20% of the population (about 60 million people) would be killed outright, and another 16% injured (about 40 million people). They also found that a war between India and Pakistan using one hundred weapons (about half their current arsenals) with fifteen-kiloton yield, exploded on cities on the basis of population, would kill or injure about 45 million people.

The eventual build-up to more than thirty thousand American warheads and forty thousand Soviet warheads, most with more than ten times the yield of the Hiroshima weapon, was gross overkill. There are simply not that many targets. U.S. targeting strategy is highly classified. However, recently revealed nuclear targeting documents show that in 1959 population was treated as a distinct target for U.S. nuclear weapons (Shane, 2015). Yet, even in a counterforce war, in which population is not directly attacked, substantial civilian casualties will occur because military and industrial targets are both located in urban areas. For instance, Bush et al. (1991) and Small (1989) considered a counterforce[3] attack by Russia on 3030 leading U.S. targets such as U.S. Army, Navy, and Air Force bases; fuel storage locations; refineries and harbors (but not missile silos or launch-control facilities) with five-hundred-kiloton warheads. In fact, because of the significant area destroyed by a nuclear bomb explosion, there were only 348 unique targets in these studies that were on average each attacked by 8.7 weapons when 3030 weapons were used. While cities were not targeted directly, 50% of the U.S. urban areas were destroyed.

There are only about 300 cities in the United States, and 180 in Russia with a population greater than 100,000. There are about 60 cities in Pakistan, 365 in India and 445 in China with a population greater than 100,000. It might require more than one weapon to destroy some large cities, and there are some important targets in rural areas. Nevertheless, the two thousand strategic deployed weapons in both the American and the Russia arsenals under current treaty still allow them to destroy the bulk of any adversary's infrastructure and population given the likely assumption that the majority of the weapons detonate. The current arsenal of India is great enough to attack almost every moderate-sized city in Pakistan two times.

This sort of gruesome calculation of the numbers of weapons needed to destroy an adversary has likely been repeated in many nations. In terms of the numbers of weapons in Figures 24.1 and 24.2, and the numbers of cities in the world that might be targets, the number of weapons may be chosen by most countries to ensure they can bomb every moderate-sized city of any country in the world that they choose. The emphasis in sizing nuclear arsenals is on ensuring a level of destruction, not a level of survival.

Unfortunately, the collateral damage from using these weapons may be much greater than the direct damage. Therefore, ensuring the destruction of any adversary, and giving no consideration to how many might survive, may lead to the accidental deaths of most of the world's population.

24.3 Self-Assured Destruction

Nuclear weapons cause damage through prompt and delayed nuclear radiation, thermal radiation and shock waves. Prompt radiation arises from the nuclear fireball and the nuclear reactions producing the detonation. Delayed radiation is from the fallout containing the radioactive daughter products of the nuclear explosion. Thermal radiation is a bright pulse of light emitted by the explosion. Shock waves are high winds and associated pressure fluctuations that occur over very short periods. It is difficult to untangle the direct damage from prompt radiation, thermal radiation and shock waves because their zones of influence overlap near ground zero. Delayed radiation could kill large numbers of people in areas downwind of ground bursts, which might be used to attack missile silos. Ground bursts near the surface (as opposed to being deeply buried) lift relatively large soil particles into the air. Radioactive particles attach themselves to these dust particles, and when they fall out of the atmosphere onto the ground (hence the name "fallout") within hours or days, they can expose the population at the surface to dangerous levels of radiation. However, even with ground bursts, the casualties from delayed exposure to radiation are likely to be less than those from the other direct effects in an attack on a city. An attack on a missile silo, or other unpopulated area, might have the majority of casualties from delayed radiation. Airbursts are generally more destructive than ground bursts because the area impacted by prompt radiation, thermal radiation and shock waves is larger. Therefore, combatants are likely to use airbursts unless they are attacking buried targets. The debris from airbursts generally contains little material of large enough size to fall out of the atmosphere quickly. Therefore, the nuclear radiation largely decays before it reaches the surface and is less of a hazard to people than material that falls out rapidly. If your goal is killing people, an airburst over a city is more effective than a ground burst that kills fewer with prompt radiation, thermal radiation and shock waves and more with delayed radiation.

Following a nuclear explosion the shock waves knock down structures. These ruptured buildings will experience myriad small fires, which can coalesce into a firestorm. The thermal radiation from the fireball can also set fires over a wide area. One does not need a nuclear weapon to initiate a firestorm. For example, the United States and its allies purposefully set many firestorms in urban areas in World War II, including at Dresden, Hamburg, Tokyo and several other Japanese cities, using hundreds of aircraft carrying incendiary bombs. There have also been damaging firestorms after earthquakes, such as the 1906 San Francisco earthquake. It is believed that fires rather than the earthquake caused the vast majority of the damage to that city. The energy released in firestorms is immense. For instance, Toon et al. (2007) estimated that the energy released in the Hiroshima firestorm, which reached full strength several hours after the nuclear explosion, was about one thousand times greater than the energy released in the nuclear explosion.

Firestorms are self-feeding fires that suck air into themselves, and generate immense columns of rising smoke. There are many observations of stratospheric injections of smoke from large intense forest fires, which are similar to urban firestorms (e.g., Fromm and Servranckx, 2003). Once the smoke is about ten kilometers (approximately six miles) above the ground, sunlight will heat the smoky air and it will rise; this is called self-lofting. Observations may have recorded smoke from forest fires rising by self-lofting to twenty kilometers above the surface (de Laat et al., 2012), and models suggest large smoke injections in a nuclear conflict could reach fifty kilometers above the ground by self-lofting. At altitudes above about twenty kilometers it never rains, so the smoke would remain in the air for years. The clouds from very large volcanic eruptions are observed to remain in the stratosphere for a few years, but they have only a small amount of self-lofting because their semi-transparent particles do not absorb much sunlight.

Toon et al. (2007, 2008) discuss the amount of smoke produced by varying numbers of nuclear weapons exploding in different countries around the world. The amount of black carbon (or soot) is the key factor in the climate calculations. Toon et al. (2007) suggest that in a war between India and Pakistan involving one hundred Hiroshima-sized weapons about 7 million tons of black carbon could be produced. Toon et al. (2008) suggested that a war between the United States and Russia involving forty-four hundred strategic weapons, close to what is allowed by current treaties, with 100,000-ton yield each would produce about 180 million tons of black carbon. Robock et al. (2007) investigated the climate changes after the injections of 50 or 150 million tons of black carbon. The 150-million-ton case produced global average temperatures more than 8 °C cooler than normal, which is well below the average temperature found in the last ice age. Mid-latitude grain growing regions had simulated temperatures below freezing every day for one or two years. Clearly, injecting 150 million tons of black carbon into the stratosphere creates a climate catastrophe.

A recent study of the aftermath of a nuclear conflict (Mills et al., 2014) used an Earth system climate model including atmospheric chemistry, ocean dynamics as well as interactive sea ice and land components to investigate the environmental damage from a limited regional nuclear war between India and Pakistan. Stenke et al. (2013) performed a similar study. Pausata et al. (2015) considered the importance of the length of the conflict, and of adding organic material to the 5 million tons of black carbon. Weakly light-absorbing organic material dominates the black carbon in smoke by a large factor. For the same assumptions about the length of conflict and materials injected these three studies produced similar climate changes. Mills et al. (2014) assumed each side detonated fifty weapons with fifteen kilotons of yield for each weapon over urban areas. One hundred total weapons is about half of the total current arsenals of India and Pakistan. These urban explosions are assumed to start one hundred firestorms producing a total of 5 million tons of smoke. In the computer simulation this smoke self-lofted from the upper troposphere to the stratosphere, where it spread globally. The smoke produced a sudden drop in surface temperatures of about 1.5 °C, because the smoke blocked sunlight from reaching the surface, and intense heating of the stratosphere, because the smoke absorbed sunlight. The results showed that about one-third of the smoke was removed after about nine years. In the hot stratosphere, ozone was destroyed by chemical reactions. Global ozone losses of 20%–50% over populated areas, levels unprecedented in human history, would accompany the coldest average surface temperatures since the waning phases of the last ice age, thousands of years ago. Ozone in the stratosphere protects us from the harmful effects of solar ultraviolet light. Mills et al. (2014) calculated summer enhancements in ultraviolet solar exposure indices of 30%–80% over mid-latitudes, suggesting widespread damage to human health and agriculture, as well as terrestrial and aquatic ecosystems, though the effects of enhanced ultraviolet light are poorly understood since such enhancements have never been observed. Killing frosts would reduce growing seasons by ten to forty days per year for five years at mid-latitudes. Surface temperatures would be reduced for more than twenty-five years. The long period of cold temperatures is due to thermal inertia from the cooled ocean waters and to extra reflection of sunlight back to space by expanded sea ice.

Large global decreases in ozone have not been observed in human experience, though there is a significant latitudinal gradient in ultraviolet intensity. It is known, for instance, that the incidence of skin cancer in people with light-colored skin increases with decreasing latitude as a result of increasing ultraviolet light (e.g., Fears et al., 1976). The ultraviolet light is greatest in the tropics because the sun is more intense there and because there is less ozone in the tropics than elsewhere. While we know that enhanced ultraviolet light is hazardous, its effects are not yet included in agricultural models, so it is not possible to gauge its impact on food supplies or the environment. On the other hand, we have a lot of experience with the effects of changes in

Table 24.1 *Loss of Agricultural Productivity Following a Regional Nuclear Conflict with 100 Warheads*

	First 5 years	Second 5 years
U.S. maize	–20%	–10%
U.S. soybeans	–15%	–10%
China maize	–15%	–10%
China middle season rice	–25%	–20%
China spring wheat	–25%	–20%
China winter wheat	–40%	–25%

Özdoğan et al., 2013: Xia and Robock, 2013; Xia et al., 2015

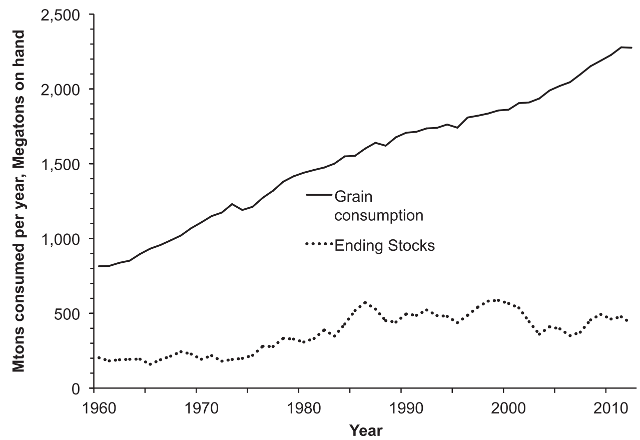

Figure 24.5 The worldwide consumption of grains and the ending stocks from 1960 until 2012 are shown. Data from Earth Policy Institute (2012) (from Toon et al., 2017).

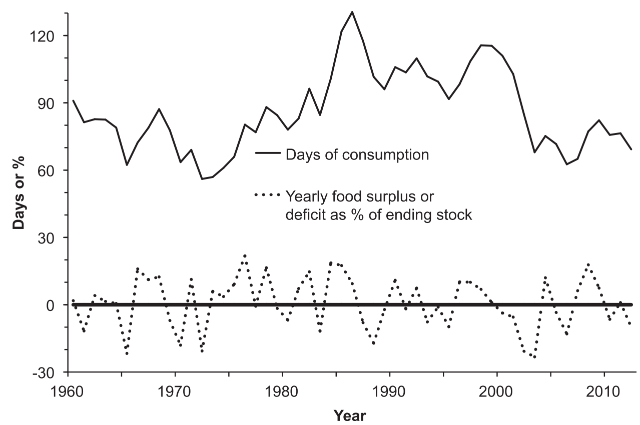

Figure 24.6 The number of days that the ending stocks could supply world food consumption, and the surplus or deficit of food as a percentage of the ending stocks are shown. Data from Earth Policy Institute (2012) (from Toon et al., 2017).

temperature and precipitation on agriculture. Table 24.1 provides some calculated crop losses due to temperature and precipitation changes following a regional war with one hundred weapons. The crop declines are mainly due to reduced temperatures and shortened growing seasons. These crop declines do not consider social feedback; for instance, farmers may abandon their land if they think it is poisoned by radiation or may concentrate on feeding their local communities rather than exporting food. Harwell et al. (1986) provide a detailed discussion of the effects of breakdown in transportation, difficulty obtaining fuel for farm machinery, disruption of grain markets and economic aspects of farming such as obtaining loans for planting food as well as many other issues. These social responses can be extremely important to the food supply, possibly even more important that the direct effects of climate on agriculture.

There are no studies on the effect of crop losses such as those shown in Table 24.1 on human society. However, there are several reasons to think they would be devastating. The world does not recognize the biblical warning by Joseph to the pharaoh of Egypt to store grain for seven years of famine. Instead, the total world grain storage, as shown in Figure 24.5, would be consumed in around seventy days at the current rate of consumption (Figure 24.6). As shown in Figure 24.5, consumption has steadily risen since 1960 as world population increased, but ending food stocks, which represent food storage, have leveled out since about 1985. Food production and consumption are closely balanced, and the food surplus or deficit is a small fraction of ending stocks (<23%) in the past fifty years, as shown in Figure 24.6. The small ups and downs of the ending stocks curve in Figure 24.5 represent the accumulation of the year-to-year variations in the production of grains relative to their consumption. Recently food consumption has tended to exceed production slightly, so ending stocks are slowly trending downward in Figure 24.5. Given the rising population, the days of food on hand figure has declined about a factor of 2 in the past decade to less than seventy days at present as shown in Figure 24.6.

Table 24.1 suggests, from the limited studies done so far, that a regional nuclear conflict between India and Pakistan might reduce global grain production 20% for five years and 10%–15% for another five years. A 20% reduction in grain production today would represent about 450 Mton of grain each year, which is comparable to the ending stocks on hand in 2012. This would be an unprecedented loss of food, exhausting the global food storage in one year, and could not be made up, since the loss would continue for a decade.

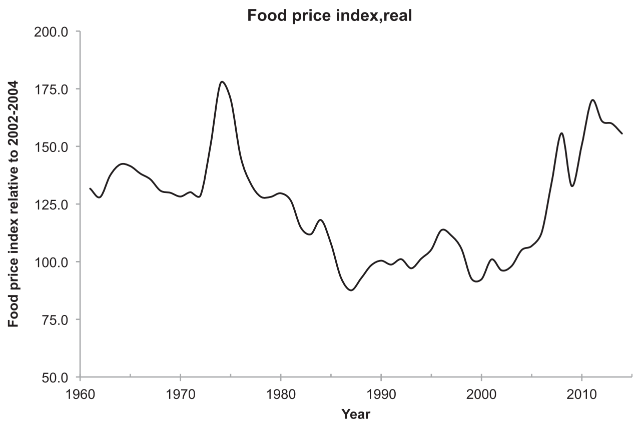

Figure 24.7 U.N. Food and Agriculture Food Price Index, based on data from Earth Policy Institute, Monthly Food Price Indexes, January 1990–January 2014, updated 6 February 2014 is shown (from Toon et al., 2017).

How would the world respond to a sudden global decline in food? Some clues are given in Figure 24.7, which illustrates an inflation-corrected food price. The Food Price Index is an estimate of the relative costs of meat, dairy, grains, oils and sugar. Historically the highest price was in the early 1970s, which corresponds to a time when Figure 24.6 indicates there was a minimum of days of food consumption near fifty-six days. There is a recent period of a relatively high Food Price Index with peaks in 2008 and 2011 and a new minimum of days of food consumption.

Analysis of the 1970s peak in the price of food indicates that a major cause was a drop in agricultural production, particularly in Russia, that was partly compensated by the United States' selling Russia the equivalent of 30% of the U.S. wheat production in the previous few years. The food price jump was exacerbated by decisions made by various political bodies (e.g., Schnittker, 1973). Although apparently unrelated in cause, the Arab oil embargo coincided in time, and drove energy prices to record levels, causing fuel rationing and other disruptions across the globe.

The 2008 food price peak followed another low point in the days of food consumption near sixty-three, and another runup in energy prices. These changes were coupled with the increased use of biofuels, which diverted about 100 million tons of maize away from food; wheat growing failures in Australia; an increased consumption of meat in China and various types of speculation and political manipulation. In the case of rice, India and Vietnam stopped exporting rice, a policy that may have been due to internal political manipulations in India and speculation in Vietnam. The loss of two of the world's largest rice exporters caused a cascade of panic in rice-importing nations (Slayton, 2009). Whatever the cause, the rise in food prices coincided with food riots in a number of countries and significant numbers of deaths in those riots (Lagi et al., 2011). The government of Haiti was overthrown in 2008 during food-related riots, and there were bread riots in Egypt in 2008 (Sternberg, 2013).

The 2011 spike in the Food Price Index may have had even more dramatic impacts on world affairs. In 2010 Russian wheat production fell 32.7%, Ukrainian wheat production fell 19.3%, Canadian wheat production fell 13.7% and Australian wheat production fell 8.7% (Sternberg, 2013). In the fall of 2010, China experienced drought and began to purchase wheat, driving up prices. People in Middle Eastern and North African countries spend large fractions of their income on food. Libya, Jordan, Algeria, Tunisia, Yemen and Egypt are each in the range of 35% to 44% of income spent on food. A large fraction of the food is bread. A significant causal factor in the Arab Spring uprisings, beginning in December 2010 and still ongoing today, was food insecurity, which was due to the wheat failures in 2010 (Sternberg, 2013). Since 2010 rulers have been forced out of power in Tunisia, Egypt, Libya and Yemen. There have been uprisings in Bahrain and Syria and major protests in Algeria, Iraq, Jordan, Kuwait, Morocco and Sudan. The ongoing conflict in Syria may have had its roots in agricultural losses within Syria.

The production failures in recent decades pale in comparison to those that might follow a nuclear conflict between India and Pakistan. In that case, the world grain storage might be eliminated in the first year after a war, and a deficit of 10%–20% might then occur for a decade. Helfand (2013) estimated that 2 billion people who are now only marginally fed might die from starvation and disease in the aftermath of a nuclear conflict between India and Pakistan. A conflict in the future with more weapons or between other powers with more weapons could be much worse.

Scientists working with nuclear weapons have understood since the dawn of the nuclear age that nuclear explosions would create fires if there were flammable materials at the site of the explosion (e.g., Eden, 2004). For this reason the more than five hundred aboveground nuclear tests were conducted in deserts, or on islands, so that there was little fuel to ignite a fire. A firestorm did occur at Hiroshima after the nuclear explosion, and there were numerous firestorms set by conventional weapons during World War II. However, during World War II the number of firestorms was much smaller than the one hundred considered by Mills et al. (2014) as being important. Also the firestorms in World War II were spread out over a year or more, so their impacts were not cumulative. Finally, during World War II there was little priority put on stratospheric observations, and instruments of that day were not sensitive enough to observe any injections of smoke into the stratosphere. The 1.5 °C cooling found by Mills et al. (2014) for a war between India and Pakistan would be much larger than the natural year-to-year variations in global average temperature and easily observed. However, the injection during World War II of only a few percent of the smoke assumed by Mills et al (2014) would produce a temperature change that would be difficult to detect even now with a functioning global temperature measurement system. For these reasons we do not have any experimental confirmation of climate effects from firestorms in World War II.

24.4 Scenarios for War

The United States and Russia remain in "launch on warning status" which means that the leaders of these countries are constantly prepared to launch some of their nuclear missiles within a few moments of learning that missiles from the other side are headed their way. This is a very dangerous situation. There are numerous examples of each side's mistakenly thinking the other has initiated an attack, and war has been narrowly averted by identifying or discounting the mistake (Union of Concerned Scientists, 2012). For example, on 25 January 1995 the Russians detected a missile launch off the coast of Norway, which they interpreted to be the start of a nuclear attack. Fortunately they did not observe other missile launches and declared it a false alarm. It was a routine scientific rocket launch, which had not been reported properly in advance through the Russian system. On 26 September 1983 Soviet early warning satellites detected five land-based missile launches. Fortunately, the officer on duty decided this must be an error since it seemed improbable that an attack would involve only five launches. It was later found that the false signals were due to reflections from clouds. It is fortunate that only five reflections were detected. Launch on warning is partly based on the need to launch land-based missiles before they are attacked by a nuclear adversary. Such missiles, whose locations are well known, are destabilizing because of this need to use them on short warning.

In Asia, a number of analyses have been conducted of how a war might start. For instance, Lavoy and Smith (2003) discuss three plausible scenarios for a nuclear war between India and Pakistan. India has conventional military superiority. India is also geographically much larger than Pakistan so parts of its nuclear arsenal are currently out of range of Pakistan's forces, while all of Pakistan is easily reached from India. One possible route to nuclear war involves a conventional conflict between India and Pakistan. If Pakistan perceived that India were about to invade, that could put pressure on Pakistan to launch its nuclear weapons before they were overrun by the superior Indian forces. Another possibility for starting a nuclear conflict is that India or Pakistan could lose control of its command and control structures as a result of an attack on them by the other side, or possibly an attack by terrorists. In such a scenario it is not clear who might be in control of the nuclear forces and what steps they might take. A third possibility for starting a nuclear conflict is that India or Pakistan might mistake an attack by conventional forces, or even military exercises, for an attack by nuclear forces. Both countries have ballistic missiles and aircraft that are potentially dual-use between conventional and nuclear weapons, making any attack ambiguous.

Another point of future conflict could involve North Korea. It is not clear that North Korea currently has operational nuclear weapons, though it has tested nuclear explosives. It is also not certain that North Korea has nuclear-capable missiles (Kristensen and Norris, 2014), though it continues to test long-range missiles and submarine-launched missiles and does have nuclear-capable aircraft. Fortunately, no other countries with nuclear weapons are near North Korea, except China, with which North Korea is allied. Factors that might trigger a nuclear conflict involving North Korea have some parallels with the Pakistan/India situation. North Korea has a much larger military than South Korea, including the U.S. troops stationed in South Korea, and Seoul is only fifty-five kilometers from the North Korean border. It would, therefore, be possible, even easy, for North Korea to overrun South Korea in a sudden conventional attack, possibly triggering a nuclear attack by the United States. Hayes and Cavazos (2015) have analyzed some of the many possible scenarios for a nuclear conflict involving North Korea. Generally, they conclude that North Korea does not have the capability to launch a nuclear attack at present, but may have in the near-future. While North Korea is expanding its capabilities it is difficult to find a scenario in which they could launch a first-strike conventional or nuclear conflict and not expose themselves to devastating nuclear retaliation, even in the future. However, the North Koreans may not analyze the situation in the same ways that are used in the West; their leadership might not be rational; there is the potential for the regime to be overthrown, leading to nuclear weapons use in North Korea itself and it is possible that North Korea's continuing provocations of their neighbors might lead to an attack on North Korea. For example, North Korea torpedoed and sank the South Korean warship *Cheonan* on 25 March 2010, which might have been considered an act of war (BBC News, 2010). It is also possible in the near-future that North Korea may calculate that they can launch a conventional attack on South Korea, while preventing a retaliation from the United States by threatening the United States with a nuclear attack on its territory. Any of these possibilities, and several others, might lead to the use of nuclear weapons.

There are numerous other scenarios that could lead either to a nuclear conflict or to further destabilization of Asia. For example, Japan or South Korea could develop nuclear weapons to defend against North Korea, likely because they lose confidence that the United States will continue to protect them. In the Middle East, Iran could obtain nuclear weapons, which would likely trigger Saudi Arabia and other countries in the Middle East to obtain them. It is hoped that the 2015 agreement with Iran will prevent the Middle East from becoming a warren of nuclear states.

Unless the world does something to build down the existing arsenals further, and stops proliferation, the remainder of the twenty-first century is likely to involve increasing risk of nuclear confrontations.

24.5 What Can Be Done to Prevent Nuclear Conflict?

No government, anywhere, is openly conducting studies to determine the damage that might be done to them in a nuclear conflict in which they are a combatant, or a bystander. There is no evidence that any current leader of any nuclear power is aware of the potential harm that might occur as a result of the environmental damage from a nuclear conflict. For example, the U.S. Nuclear Posture Review of 2010 does not mention the words "nuclear winter" nor any environmental damage that might be caused by a nuclear conflict (U.S. Government, 2010). However, the cold temperatures and the destruction of the ozone layer caused by the smoke from burning cities following a nuclear conflict, even between powers such as India and Pakistan with modest numbers of weapons compared with other nuclear weapons states, could devastate agricultural productivity, leading to mass starvation across the globe. In addition, changes in governmental stability, transportation of food, availability of fuel, functioning of economic organizations such as banks, stability of police and military authority and many other changes induced by war could be devastating to civilization. It is dangerous not to discuss these issues and risks openly in society. Such discussions might lead to lessening nuclear tensions and reductions in nuclear stockpiles.

Calculating the direct casualties from a nuclear conflict is very straightforward. The major uncertainties are the number and yields of the weapons used and their targets. There is also uncertainty about extrapolating the casualties from Hiroshima and Nagasaki to those that would occur in modern cities at various distances from ground zero. It is more difficult to compute the environmental impacts from nuclear conflicts and their consequences. However, the major uncertainties are the same as for the direct effects, the number and yields of the weapons used and their targets. The size and duration of resulting firestorms are uncertain since we have no modern examples. In addition, the amount of fuel burned, the amount of smoke emitted and the amount of smoke removed in local precipitation are uncertain. Uncertainty does not mean that the impacts have been overestimated. It is just as likely that the effects have been underestimated. As in many other areas of human endeavor, uncertainty is unavoidable when predicting the outcome of possible nuclear wars. However, when gambling with the future of human civilization it is not wise to ignore the possibility of nuclear winter by hoping that no country will ever use its arsenal.

Goldstein (2017) argues that politicians do not care about the predictions of models, and use science only to manipulate events. However, the Montreal Protocol, which is based on modeling showing that the release of certain chemicals is destroying the ozone layer, has eliminated industrial emissions of ozone-destroying chemicals. The Intergovernmental Panel on Climate Change, which is largely based on models for future climate, is currently pushing a revision of the Earth's energy production system. These are very large changes caused by scientific recognition of a problem, and wrought by statesmen who have taken science very seriously. Of course, in both these examples there was also evidence that the Earth was being impacted, such as the Antarctic ozone hole, melting glaciers, rising sea level and rising temperatures. Nuclear war is not approachable by experiment or observation. Nevertheless, there is no reason to be pessimistic and assume that politicians cannot understand the advice about the dangers of nuclear wars from their scientific establishments, or will not act on that advice. History shows, even in the case of nuclear weapons, that statesman and stateswomen will understand these dangers if they are told of them, and act appropriately.

In the early 1980s studies of the environmental effects of a nuclear conflict played a role in causing the leaders of the United States and of the Soviet Union to reduce their arsenals. Soviet leader Mikhail Gorbachev observed "Models made by Russian and American scientists showed that a nuclear war would result in 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" (Hertsgaard, 2000). U.S. President Ronald Reagan (New York Times, 1985) noted that

> a great many reputable scientists are telling us, that such a war could just end up in no victory for anyone because we would wipe out the earth as we know it. And if you think back to . . . natural calamities - back in the last century, in the 1800's, . . . volcanoes – we saw the weather so changed that there was snow in July in many temperate countries. And they called it the year in which there was no summer. Now if one volcano can do that, what are we talking about with the whole nuclear exchange, the nuclear winter that scientists have been talking about? It's possible.

As an inital step forward from our present status toward a world that is free of the threat of a global nuclear catastrophe, we suggest that the nuclear-armed states collectively engage in a dialog on the impacts of nuclear conflicts. There is precedence for such a dialog in two formats. Just prior to the build-down in nuclear weapons illustrated in Figure 24.1 and the pause in the creation of new nuclear states illustrated in Figure 24.3 the scientific academies of the world conducted a study of nuclear conflicts under the umbrella of the U.N. Scientific Committee on Problems of the Environment, as reported by Pittock et al. (1986) and Harwell and Hutchinson (1986). Of course, it is not just scientists who need to participate in this discussion. During the early 1980s a vibrant debate about nuclear weapons took place among a wide variety of interest groups including physicians, politicians, philosophers and poets. These scientific and public debates led to the build-down in nuclear weapons beginning in the mid-1980s and illustrated in Figure 24.1. We suggest that there be a new study of the consequences of nuclear conflict, as also recommended by Jeanloz (2015).

The study should not only consider the consequences of conflicts, but also address whether the reasons cited to develop nuclear weapons are valid. For example, Japan and South Korea do not have nuclear arsenals, while North Korea does. There is no evidence that North Korea is technologically superior in any way, has a greater place in any facet of world decision making or has a greater influence on any aspect of world affairs. It could also be argued that North Korea is no safer because of nuclear technology. The same opposing army is still in South Korea that was there prior to North Korea testing nuclear weapons. Indeed, sanctions placed on North Korea because of its nuclear weapons program, which may not have impacted its nuclear weapons program, have damaged its economy (e.g., Kim, 2014). Likewise, India's possession of a nuclear arsenal has not helped it gain entry as a permanent member to the U.N. Security Council. While India is recognized for its many prominent scientists and thinkers in a variety of peaceful fields of study, its nuclear program has done nothing to gain it respect as a technological power in the rest of the world. Pakistan's nuclear weapons have not helped it solve its dispute with India over Kashmir; nor have they prevented other nations from bombing its citizens and making armed military raids to seize militants located in its territories. Each of these examples, and many others, of whether the possession of nuclear weapons has achieved the goals of the country with the weapons is worthy of debate.

India and Pakistan are engaged in a rapid build-up of nuclear weapons, which is a danger to them both, and to the rest of the world. While dialogs between these nations on a variety of issues, such as Kashmir, have taken place for decades, little progress has been made. Possibly a detailed analysis by their own scientists and scientists of other nations of the consequences of a war will aid them in constructive discussions on reducing nuclear weapons instead of expanding their arsenals. Of course, these studies should include an analysis of conflicts involving all the nuclear-armed nations and consider all of their arsenals.

History shows that nuclear weapons do not achieve the goals envisioned by the states that have them. Not even a single weapon can be used given the potential for escalation to the use of many more weapons that could lead to a nuclear winter. Such escalation is particularly likely because of the eighteen hundred weapons on high alert in the United States and Russia that could be used on short notice. A war cannot be fought given the adverse impacts on the food supply of all nations of the world, including the ones who used them. The case of Pakistan's invasion of Kashmir after its test of nuclear weapons, and the entire Cold War, show that nuclear arsenals do not provide cover for unopposed conventional warfare. The Argentinean invasion of the Falklands and the Yom Kippur War show that possession of nuclear weapons does not stop invasions of nuclear nations by non-nuclear nations. The Vietnam War and the Soviet–Afghan War show that nuclear weapons do not help win wars, since in both wars the nuclear power lost. The weapons do not confer immunity from meddling by others in internal affairs, nor give countries with them enhanced access to world government. On the contrary, the weapons are very expensive to obtain and maintain. The weapons expose their possessors, and the rest of the world, to the potential for terrorists to obtain and use them. There is a significant risk, particularly between India and Pakistan, of nuclear conflict starting from misunderstanding, or misinterpretation of the other country's actions. A large fraction of the world population, inside and outside the combat zone, could die from such errors. It would behoove each nuclear weapon state to get rid of its nuclear weapons before it is too late.

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Internet Resources and Notes

[1] http://www.nuclearsecurityproject.org. Quote obtained May 28, 2014.

[2] The explosive energy released in a nuclear detonation is measured in relation to an explosion of the equivalent weight of the conventional explosive trinitrotoluene (TNT). The explosive power in all bombs used in WWII combined, including the atomic bombs dropped on Hiroshima and Nagasaki, was several megatons, which could now be released by just one high-yield nuclear weapon.

[3] In the lexicon of military targeting there are countervalue, counterforce, and rational wars. Rational wars use a small number of weapons to attack targets of symbolic value. Countervalue wars use massive attacks on urban areas to destroy economic and social infrastructure. Counterforce wars involve massive attacks on military, economic and political targets. In reality, countervalue and counterforce wars end up attacking much the same targets, especially for large numbers of high yield weapons.

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