

# ***EARTH UNDER SIEGE***

**From Air Pollution to Global Change**

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*with a Foreword by Carl Sagan*

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# 14

## Global Environmental Engineering

The daunting environmental problems—local, regional, and global—discussed in the previous chapters must be solved, or at least controlled, if human civilization is to advance and prosper—if people everywhere are to achieve an acceptable standard of living and comfort. Most of the identified problems are associated with the widespread application of technology, particularly for the production of energy. Such technologies are deeply ingrained in economies and ways of life. Constituencies may seek to regulate the most offensive activities, but often these regulations are circumvented. Over the long haul, alternative sources of energy will need to be found. But what can be done in the meantime to preserve a decent quality of life? This chapter considers the emerging issue of **global environmental engineering (GEE)**, which seeks technological cures to solve intractable environmental problems or to preserve as the status quo a degraded state of a declining environment.

GEE might be looked on as the next logical step in the coevolution of human intelligence and technology (Section 4.4). This coevolution has created a profound codependence between society and technology. In seeking solutions, it is difficult to evolve in reverse, to recede to an earlier state. The answer always seems to lie ahead in new technology. That, in turn, leads to deeper dependence. Is technology like heroin? Or Valium? Are we headed for a painful siege of withdrawal or a stuporous afternoon at the mall? Should we be so optimistic, complacent, or shortsighted as to presume that a livable environment can be maintained in the face of increasing pollution through increasing doses of technology?

and the quality of life have fallen backward only during episodes of global warfare. Achievements in science and technology have surged. Everyday conveniences abound, and sophisticated helpmate devices, like refrigerators and washing machines, are now taken for granted. One problem that cannot be ignored, however, is pollution of the environment as a by-product of population growth and technology. Garbage littering roadways and waterways is too visible to overlook; smog blanketing cities is too thick to see through. Subtle changes in the ozone layer and in the climate promise an uncertain future.

As a newspaper headline declared recently, “Tinkering with the environment is tempting.” It is often seen as much easier to compensate for harmful behavior than to modify or stop the behavior. Smoking is a bad habit. But rather than suffer the discomforts of nicotine withdrawal, many people would rather puff on “low-tar” cigarettes and use a breath freshener. The long-term damage is rationalized in terms of short-term pleasure or profit. If an antidote for the effects of chlorofluorocarbons (CFCs) on stratospheric ozone could be found, it would be much easier to continue manufacturing refrigerators that use CFCs than to redesign refrigerators to run on more complex and expensive compounds requiring new manufacturing techniques. The antidote itself might be expensive and cause tertiary environmental problems, but how much easier it would be to stay with the old way of life. If the ozone layer is depleted, new crops can be genetically engineered to survive the increased ultraviolet radiation. If aggressive pathogens emerge to ravage the crops, stronger pesticides can be developed. If those pesticides kill birds well, that may just be the cost of human survival.

### 14.1 What Is Global Environmental Engineering?

In this century, the wealth and health of the human species have steadily increased. Standards of living

#### 14.1.1 LIVING THERMOSTATS: NATURAL COMPENSATION

Nature has evolved complex systems that exhibit self-control. Many natural systems are internally

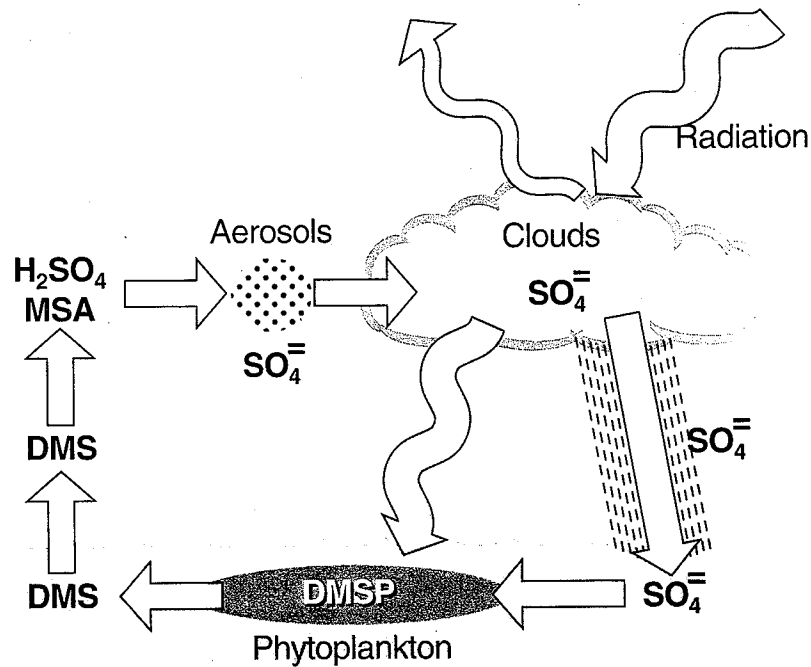


Figure 14.1 Example of a natural climate control mechanism. Dimethyl sulfide (DMS) released by phytoplankton in ocean surface water enters the atmosphere and is oxidized, forming sulfate aerosols that alter the reflective properties of marine stratus clouds and hence modulate the solar insolation at the ocean surface where the phytoplankton live. The chain of events leading back to phytoplankton is impressively complex and poorly understood. (Adapted from R. Charlson, J. Lovelock, M. Andreae, and S. Warren, "Oceanic Phytoplankton, Atmospheric Sulfur, Cloud Albedo, and Climate," *Nature* 326 [1987]: 655)

controlled by physical, chemical, and biological processes that limit the number of variations the system can accommodate. The climate system, for example, has a number of built-in feedback mechanisms, involving oceans and clouds, that help damp large climatic swings (Section 11.5). Groups of organisms coexisting in ecosystems are balanced by the availability of nutrients and by relationships between predator and prey.

An example of a naturally occurring mechanism that may influence the climate is illustrated in Figure 14.1. The mechanism involves the compound dimethyl sulfide (DMS), which is produced by phytoplankton in the oceans' surface waters. The sequence of events and their impact on the overall climate, triggered by the production of DMS, are quite complicated. DMS seeps from the ocean into the lower atmosphere—the marine boundary layer. That fact has been ascertained by measurements of DMS taken in air over regions where phytoplankton are active. The DMS is subsequently oxidized to form sulfates. This is known from laboratory studies and analyses of marine atmospheric chemistry. The sulfates form new aerosols, a process that has been

demonstrated by observations of particles over the oceans. These new aerosols affect the properties of marine stratus clouds that condense on the aerosols. This effect is less certain. Unusual behavior of marine clouds has been observed following the passage of ships: The smokestack emissions create long-lived "tracks" in the clouds. The appearance of ship tracks suggests that DMS emissions may have a similar effect on marine clouds.

The *climate* connection to dimethyl sulfide is still far away. The DMS-generated aerosols can modify the reflectivity, or albedo, of marine clouds (Section 11.6.5). In particular, the affected clouds can become more reflective. This modification has been noted in satellite observations of clouds over the oceans with ship tracks embedded in them. According to the discussions in Sections 11.6.4 and 11.6.5 (also see Section 14.3.2), it follows that an increased albedo tends to cool the climate. Thus a possible connection between the production of dimethyl sulfide by phytoplankton and a change in climate can be established.

There are two important questions that remain unanswered, however. Is the effect of DMS produced

by plankton large enough to be important on a global, or even a regional, scale? And is the feedback loop closed; that is, does the climatic change caused by the DMS in turn affect the phytoplankton and their rate of production of DMS and hence the aerosols, and so on back to the climate?<sup>1</sup> In other words, is there a continuous cycle of cause-and-effect that may either amplify or diminish the climatic signal? Scientists simply do not yet know the answer to this crucial question, although it is likely that the DMS-climate connection is very weak.

The DMS-cloud relationship, which represents a rather small part of the global climate system, demonstrates the extraordinary complexity of the natural world. Myriad physical, chemical, and biological factors must be understood before quantitative predictions are possible. When a new technology inadvertently throws one process out of kilter, entire systems can be disturbed. The means chosen to correct the problem should rely on knowledge of the entire system. But most frequently, that is not the case.

#### *Alternative and Corrective Technologies*

Technology has inarguably upset natural checks and balances in a number of important systems. Since technology created these problems, it is reasonable to consider whether technology can provide solutions. There are two approaches that seem worthwhile to pursue: alternative technologies and corrective technologies. **Alternative technologies** should offer nonpolluting substitutes for currently polluting activities. **Corrective technologies** should provide complementary means to fix problems associated with other essential activities. Alternative technologies replace undesirable products and activities with more desirable ones. Corrective technologies attempt to compensate for, or mask, the original problem.

1. Positive and negative "feedback" are important to determining the behavior of complex or coupled systems. Think of a *positive-feedback loop* as reinforcing or in "phase." Psychologists use positive feedback—praise or a reward—to reinforce desired behavior. A *negative-feedback loop* is usually more stable; it strongly limits the possible excursions that the system can take. Negative feedback is commonly used in electronic circuits to ensure stable output signals. In the climate system, positive feedback amplifies small perturbations, and negative feedback dampens perturbations, like shock absorbers on a car.

#### *It's a Big World After All*

It is relatively easy to dream up schemes for improving the environment or compensating for pollution. The scientific basis for such schemes must be verified, of course, and all possible side effects—both good and bad—must be identified. The world population requires reassurance. Even putting these issues aside, however, another crucial question must be considered in all concepts for altering the global environment: Is the scheme even practical in terms of engineering technology and total cost? The enormous scales of these problems are not often understood by the polluters or the proponents of solutions.

Think of the numbers. The sun continuously deposits roughly 100 million gigawatts of power (the same as 100 billion megawatts) on the Earth. A single large power plant generates something like 1 megawatt of power. Humans collectively produce about 10,000 gigawatts (10 million megawatts), or 0.01 percent of the solar input (which explains why the energy dissipated as heat by civilization is not contributing significantly to planetary warming). Roughly 0.1 percent of the absorbed solar energy is converted by plants to chemical energy stored in biomass. That energy is released when the biomass decomposes or is burned. To fill all of society's present energy needs, about 10 percent of the existing biomass potential-energy production would need to be harnessed. Alternatively, solar-energy collectors with a total area of at least 10,000 square kilometers would be needed in orbit. That area, although not much larger than a small state, would require unprecedented activities and expenses to construct in space.

The atmosphere weighs 5 quadrillion metric tons (or tonnes); one part per billion by mass of the atmosphere amounts to 5 million tonnes. The ocean weighs 300 times as much as the atmosphere and contains heat energy roughly equivalent to 500 years of total solar input. The lower atmosphere has a volume of more than 5 billion cubic kilometers, and the stratosphere is four times larger. The surface area of the oceans is more than 300 million square kilometers. The living organisms on our planet weigh almost 1 trillion tonnes, about 200 tonnes for every living person. The ozone layer weighs 4 billion tonnes and is continually being renewed (roughly once every month).

By comparison, a large truck can carry 10 tonnes; a jumbo jet, 100 tonnes; and a large ship, 1000

tonnes. A home takes up 100 square meters; a city, perhaps 100 square kilometers. It would take all the people currently on Earth 1 million years to breathe all the air in the atmosphere. Humans and their most impressive engineering projects and structures are puny in comparison with the constructs and scales of the natural world. Yet in a number of ways, humans are damaging the global landscape by undermining or destroying critical vulnerable links and components. Like microscopic parasites that invade and weaken the heart muscle, humans are infiltrating and compromising the life-sustaining tissues of the biosphere. Can vital functions be maintained indefinitely? Or will the Earth someday need artificial organs to survive?

#### 14.1.2 PLANETARY ENGINEERING

As a human enterprise, global environmental engineering has much in common with another technological objective: the modification of other planets to make them habitable for humans. The goal of **planetary engineering** is to alter the surfaces and atmospheres of nearby objects in the solar system to mimic the environment of Earth. Future generations might even "terraform" planets in other star systems throughout the universe. To start out, however, only three objects in the solar system have the correct size and composition to construct a livable world (aside from the Earth, where the quality-of-life rating is slipping). These objects are Mars, Venus, and Titan, the largest moon of Saturn. The Earth's moon—the closest object to us and therefore the most accessible—is too small and its gravity is too weak, to retain an atmosphere. Moonites would be forced to live in space suits and domed towns. The other possible places to hang the human shingle are so remote and inhospitable that enormous investments and long-term commitments would be necessary to ensure successful terraforming projects.

Concepts for planetary engineering have arisen from the debris of global scale environmental damage on Earth. It is widely recognized that human activities are modifying the composition of the Earth's atmosphere and climate. If global-scale changes can be produced inadvertently here on Earth, why not purposefully on another world? Obviously, planetary environments *can* be altered significantly and possibly can be fine-tuned. But before embarking on

projects to make other worlds habitable, we should perhaps concentrate on preserving our only safe haven in the solar system.

In most of the planetary engineering projects that have been proposed, the same principles can be applied as in the case of global environmental engineering. In particular, the radiative balance of a world can be changed by modifying the solar insolation (with sun shades), planetary albedo (with aerosols), or atmospheric greenhouse effect (with carbon dioxide and other gases). When making the necessary modifications, the composition of the atmosphere must be maintained within certain bounds (Table 14.1). Such limits to the basic composition of the environment pertain to the preservation of life as it has evolved on the Earth. If distant worlds are to host humans and other species, those engineered environments must conform to standards established here on Earth.

Mars is a frozen world, with an average surface temperature (~220 kelvin) more than 50°C below the freezing point of water (0°C). Venus is a hot-house world whose surface temperature (~730 kelvin) is about 360°C above the boiling point of water (100°C). Titan is absolutely gelid, making Mars appear balmy by comparison, since Titan's surface temperature (~95 kelvin) lies roughly 180°C below the freezing point of water.

To change Titan into a productive and living world would certainly pose a grand challenge to the human intellect. The intensity of sunlight reaching Titan is only 1/100 of that at the Earth. With such a weak source of light, even photosynthesis would be problematic. Nevertheless, Titan is thought to be more amenable to planetary engineering because of the large masses of greenhouse-active gases condensed on its cold surface. By artificially heating the surface, these gases might be released and provide a strong positive feedback on the initial surface warming. The most efficient way to warm up Titan and evaporate its abundance of greenhouse gases could be to heat the surface directly using energy generated by nuclear fusion. The fusion furnaces would use hydrogen isotopes isolated from compounds frozen on the surface.

The intensity of sunlight on Mars is weak (Mars is much farther from the sun than Earth is [Table 11.1]), but more significantly, the Martian atmosphere is too thin to create a greenhouse warming. On Venus, the solar intensity is strong (actually about twice the intensity as at the Earth), but more

Table 14.1 Limits to Planetary Habitability

<i>Parameter<sup>a</sup></i>	<i>Limits for survival<sup>b</sup></i>	<i>Comments</i>
Temperature of the planetary surface (~15°C)	0 to 30°C	Most species cannot survive below freezing or above -30°C for prolonged periods of time, for various physiological reasons
Total atmospheric pressure (1 atmosphere)	> 0.01 atmosphere	For most plants, assuming an air like mixture of gases
	> 0.5 atmosphere	For humans, in air, based on response to high altitude
	< 5 atmosphere	For humans, owing to narcosis (suffocation) from exposure to nitrogen and other gases
Oxygen (O <sub>2</sub> ) concentration (~0.2 atmosphere)	> 0.001 atmosphere	For plants, to perform respiration
	> 0.13 atmosphere	For humans, to avoid hypoxia (lack of sufficient oxygen)
	< 0.30 atmosphere	For plants, to avoid excessive flammability
Nitrogen (N <sub>2</sub> ) concentration (~0.8 atmosphere)	> 0.001–0.01 atmosphere	For plants to ensure sufficient nitrogen fixation
	> 0.30 atmosphere	For humans, to produce adequate total atmospheric pressure
Carbon dioxide (CO <sub>2</sub> ) concentration (0.000365 atmosphere or 365 ppmv)	> 0.00015 atmosphere (150 ppmv)	For plants, minimum concentration for photosynthesis
	< 0.01 atmosphere (10,000 ppmv)	For humans, to avoid toxicity associated with long exposure

<sup>a</sup> The ambient values for Earth are shown in parentheses.

<sup>b</sup> The limiting values are rough figures corresponding to the existence regimes of common flora and fauna. <, "less than"; >, "greater than."

Source: Information from C. McKay, O. Toon, and J. Kasting, *Nature* 352 (1991): 489.

important, the Venusian atmosphere is dense with greenhouse gases. On Mars, the challenge would be creating a stable greenhouse atmosphere thick enough to hold in the dim sunlight that does arrive. On Venus, the trick would be to cool the surface and at the same time remove the greenhouse gases that might trigger a new runaway greenhouse effect (Section 11.4.4). For Mars, the solution might lie in the frozen soils and ice caps, which hold large amounts of carbon dioxide and water. For Venus, the answer might involve metallic minerals near the surface that can react with carbon dioxide to form

carbonates. For each of these planetary-engineering schemes, the scale of operations would be immense. In the case of Venus's rocks reacting with CO<sub>2</sub>, for example, the surface over the entire planet would need to be mined and processed to a depth of about 400 meters!

In the futuristic plans for planetary engineering, we should include the eventual likelihood of genetic engineering of new species. One could imagine revolutionary new microbes that could live in the concentrated sulfuric acid clouds of Venus, eating carbon dioxide and converting it to graphitic carbon

for use in creating an "antigreenhouse" effect (Section 14.2.1). Plants might be designed that could thrive on low levels of sunlight. One futurist has gone so far as to suggest that rather than engineering planets to suit people, we should genetically engineer people to suit the available planets. Any volunteers for cosmic surgery?

## 14.2 Technological Traps

Since the Industrial Revolution, society has amassed a number of basic technologies. The specific applications range from transportation and communication to energy production and medicine. We enjoy technological wonders such as television and air travel. Humans can now be rebuilt part by part (up to a point). A turkey can be cooked in half an hour.

How many people actually understand these technologies? Only a handful of scientists and engineers are familiar with the inner workings of a television set or microwave oven or nuclear-power plant. How much do we need to know? Are we sure that these technologies, which we take for granted, are safe? The industries that develop and distribute these technologies reassure us of their safety. Even so, regulatory bodies and watchdog agencies have been established to keep an eye on things. Are the scientists and engineers themselves smart enough to recognize potentially hazardous technology? If the past is any measure of skill in this regard, the answer is "Not always." Countless collapsed bridges, crashed airplanes, and sunken ships attest to the limited human ability to forecast and forestall disasters associated with technology. Even the most specialized and expensive technologies are not immune from engineering flaws; the space shuttle and the Chernobyl power plant are examples (Sections 7.3.2 and 7.3.3). On the whole, society is relatively safe; at least on the surface, that appears to be the case. The real threats of technology arise from subtle traps not yet "sprung" that lie along the path of progress.

In the following sections, we look at several well-known technological traps that have already been sprung.

### 14.2.1 NUCLEAR WINTER

The threat of nuclear war has diminished in recent years with the breakup of the Soviet Union and the

democratization of the Eastern bloc. New strategic-arms treaties have promised to reduce the superpowers' arsenals by a factor of two or more in the next decade. So everything is OK. Right?

Into the foreseeable future, thousands of nuclear warheads will remain in the hands of more than a dozen nations. The political stability of some of these nations is in doubt. The weapons caches are powerful enough to destroy modern civilization, city by city, 10 times over. In addition, the danger of a nuclear winter following the massive use of these weapons in warfare remains real, although much less likely since East-West rapprochement.

*Nuclear winter* is the name of a new phenomenon associated with the mass detonation of nuclear weapons. Nuclear winter is the deep, short-term cooling of the Earth's climate. Dark smoke generated by massive conflagrations ignited by nuclear blasts would prevent sunlight from penetrating to the ground, leading to a rapid drop in land temperatures. Agricultural crops, which are sensitive to meteorological fluctuations, would be devastated by unprecedented weather anomalies. Crop destruction would be further aggravated by the loss of transportation and other infrastructure support. In addition, concurrent environmental stresses, very likely including large ultraviolet radiation doses beneath a depleted ozone layer, would compromise plant growth. Those people that survived the initial nuclear exchange would be faced with a lack of food and water and health services, even as they were enervated by widespread radioactive fallout and a variety of other serious environmental stresses. The world after a nuclear war would probably be dominated by mass starvation and epidemics.

How could the world leadership have allowed us to get into this mess? Why has the future of humanity been placed in jeopardy? In the rapid advance of scientific frontiers during the first half of the twentieth century, physicists could hardly avoid stumbling across the secrets of the atomic nucleus and the methods for releasing the enormous energy stored there (Section 7.3.1). The design of nuclear explosives is actually quite straightforward, even if the devices are expensive to build. During World War II, a team of scientists were brought together at Los Alamos, New Mexico, to design and build the first atomic bombs.<sup>2</sup> Soon after the first successful

2. Many of the greatest physicists and chemists of this century participated in the effort to develop the atomic bomb, including Leo Szilard, Enrico Fermi, Hans Bethe, George Kistiakowski, and

detonation of a nuclear device in 1945, two of these new and devastating weapons were dropped on the Japanese cities of Hiroshima and Nagasaki. The human species lost its innocence. Mass destruction, once restricted to natural events like earthquakes and floods, could now be manufactured and delivered in small packages.

Following World War II, "national security" and "missile gaps" were invoked, on both sides of the Atlantic Ocean to justify the senseless expansion of nuclear arsenals. Politicians and bureaucracies could hardly resist wielding such a powerful stick. Businesses were not inclined to pass up opportunities to reap enormous profits at the expense of taxpayers. Minor dictators could see the value of such compact weapons of mass destruction for threatening neighbors and the world at large. The politics of nuclear weapons thus motivated a potentially self-destructive balance of terror. After 40 years and trillions of dollars spent, the world is left with tens of thousands of useless and dangerous warheads, vast areas of radioactive contamination, and hundreds of thousands of scientists, engineers, and bureaucrats trained exclusively to build, maintain, and justify nuclear weapons.

### *The Aftermath of Nuclear War*

In a nuclear burst, the fireball created by the explosion emits radiation like a blackbody emitter (Section 3.2.1).<sup>3</sup> The effective temperature of the fireball is

Edward Teller. J. Robert Oppenheimer was the leader of the Manhattan Project, as it was called. Oppenheimer and most of the other physicists later opposed the push to expand the nuclear arsenal and design new weapons of mass destruction, particularly the "hydrogen bomb." Oppenheimer was later stripped of his security clearance because of false accusations questioning his loyalty to the United States. Albert Einstein did not participate in the Manhattan Project, but was instrumental in convincing President Franklin Roosevelt to start the project, emphasizing that Germany might be seeking to build nuclear weapons to use against the Allies.

3. Nuclear weapons generate their energy from nuclear reactions, unlike conventional weapons that derive energy from the chemical reactions of "high explosives" such as TNT. Fission weapons use the same nuclei-splitting reactions as nuclear-power plants do, only in a highly controlled manner. The so-called hydrogen bomb derives most of its energy from nuclear fusion reactions, similar to those that drive the sun. To initiate a fusion explosion, a fission detonation is used to create the necessary temperatures and pressures. The weapons that destroyed Hiroshima and Nagasaki would now be mere triggers for hydrogen bombs. The power of a nuclear weapon is measured in kilotons (KT) or megatons (MT). A 1-kiloton weapon has roughly the same explosive power as 1000 tons of TNT! A 1-megaton weapon is

about 7000 kelvin, similar to the radiative temperature of the sun. The fireball light is emitted for only a few seconds as an intense **thermal pulse**. Flammable materials—paper, cloth, vegetation, fuels, and so on—close to the explosion (within about 50 kilometers for a 1-megaton [MT] detonation) can be ignited by the thermal pulse. As a result, nuclear explosions can initiate massive fires. At Hiroshima and Nagasaki, fires engulfed the areas destroyed by the atomic bombs. In Hiroshima, an unusual **firestorm** arose from the rubble of the city and consumed all combustible matter over an area of 10 square kilometers. The fierce storm generated swirling winds and temperatures high enough to fuse metal and glass.

When oil, plastics, asphalt, and many other common materials are burned, the smoke produced is exceptionally black and sooty. The individual particles of soot are typically less than 1 micrometer in size (too small to be seen by the naked eye). By comparison, fires in vegetation produce a much lighter-colored smoke, usually brownish or even white. The sooty smoke, which is always associated with city fires, has a much greater impact on sunlight than does the lighter vegetation smoke. A cloud of sooty smoke appears black because it is absorbing the impinging radiation (Section 3.2.2). However, it has also been observed that this smoke has a much smaller effect on radiation at longer wavelengths, in the thermal infrared spectral region. These unique properties of soot—strong solar absorption and weak thermal absorption—are some of the factors responsible for the nuclear-winter effect.

Following a large-scale nuclear exchange, a dense layer of smoke might accumulate in the atmosphere. It has been estimated that as much as 10 million to 100 million metric tons of sooty smoke might be generated from urban fires. Even if spread over an entire hemisphere, this would be enough soot to dim the sun at noon everywhere. Wildfires often blot out the sun hundreds of miles downwind. During the Persian Gulf War of 1991, soot from oil-well fires created nighttime during the day in Kuwait. Conflagrations ignited in hundreds of cities in a nuclear war would have a quite different character and on a greater scale. The sun might be blotted out over entire continents for weeks. Huge soot clouds would encircle the globe.

equivalent to 1 million tons of TNT, about the total amount of all the explosives used in World War II. Some individual nuclear weapons are 10 MT, and the Soviet Union tested a 50-MT weapon.



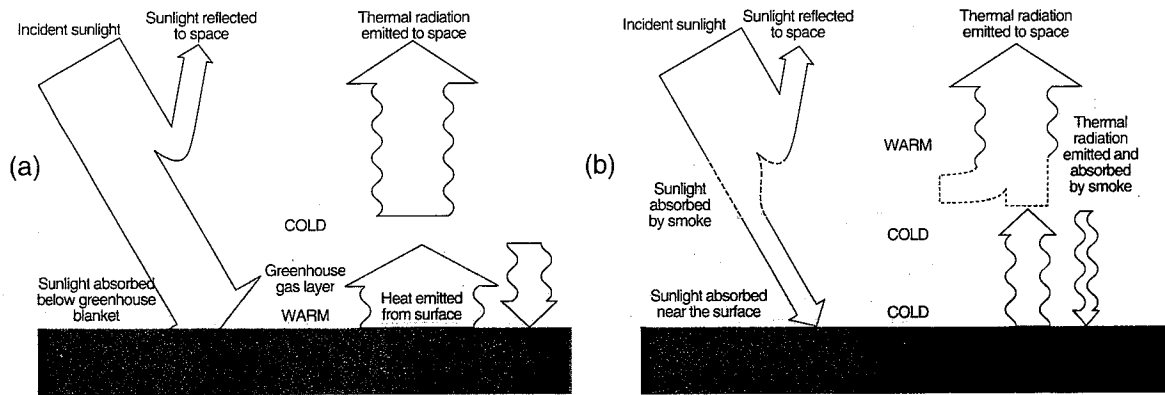


Figure 14.2 Comparison of the (a) natural “greenhouse” warming effect caused by gases in the lower atmosphere and the (b) “antigreenhouse” cooling effect produced by absorbing smoke particles in the upper atmosphere. In the normal greenhouse effect, gases and clouds trap thermal radiation created by solar heating near the surface and enhance the warming of the ground. In the antigreenhouse effect, the smoke layer blocks sunlight, reducing the heating of the surface while still allowing thermal radiation from the lower atmosphere to escape to space, cooling the surface. In the antigreenhouse effect, a large-scale temperature inversion is formed in the upper atmosphere because sunlight absorbed by smoke strongly heats the air even while the surface is cooling sharply.

In 1816, Lord Byron, wrote the poem “Darkness.” It was the same year Mary Wollstonecraft Shelley wrote her novel, *Frankenstein*. It was a glum and depressing year following the eruption of the Tambora volcano (Section 11.6.4). Byron’s poem is a premonition of global disaster occasioned by the dark clouds of nuclear winter:

The bright sun was extinguish’d ... and the icy earth  
Swung, blind and blackening in the moonless air;  
Morn came and went—and came, and brought no day,  
And men forgot their passions in the dread  
Of this their desolation; and all hearts  
Were chilled into a selfish prayer for light. No love was  
left;  
All earth was but one thought—and that was death,  
Immediate and inglorious; and the pang  
Of famine fed upon all entrails.

“Darkness”

The smoke clouds generated by nuclear fires would disrupt the energy balance of the planet. The amount of sunlight reaching the surface would be minimized. As a result, surface temperatures could drop significantly. Figure 14.2 illustrates the radiation balance for the normal atmospheric greenhouse effect and the modifications that a dense layer of soot would cause. Because of the smoke, sunlight that normally penetrates to the surface would be absorbed and reflected by the smoke particles. But the longwave infrared energy emitted by the surface and lower atmosphere could still escape because smoke

particles are not as effective at absorbing this radiation. This combination of sunlight depletion and thermal leakage would create an unusual *antigreenhouse effect*. The surface and lower atmosphere would be strongly cooled, or refrigerated. Meanwhile, the smoke layer itself would be sharply heated by the absorbed sunlight. This unprecedented pattern of continental-scale heating of the upper troposphere and cooling of the lower troposphere and surface would create a stable temperature structure, or inversion (Section 5.3). Under these circumstances, vertical mixing and turbulence would be suppressed, thereby isolating the surface and preventing it from being warmed effectively by heat transfer from warmer air layers above. Deep convection and precipitation would be inhibited. Accordingly, the nuclear winter-induced temperature inversion would limit the removal of soot from the warmer upper layers by mixing and washout, thus extending the residence time of the soot in the atmosphere.

The presence of a soot layer in the upper atmosphere and the heating of that soot by the sun represent a positive-feedback system. Heating of the soot would cause the atmosphere to stabilize, lengthening the residence time of the soot and thus allowing the heating to continue for a longer time. In addition, the heating of the soot would actually cause parcels of the soot to rise, much like hot-air balloons. The soot would thus rise higher and last longer. This additional positive feedback is referred to as a *self-lofting effect*.

*Acute Global Climate Change*

The nuclear-winter theory most likely will never be tested (if it were and if the theory were correct, the world would never be right again). However, like other environmental issues, nuclear winter can be simulated using a model. Today, there are available advanced global climate models running on advanced computers. Smoke emissions corresponding to a hypothetical nuclear exchange have been inserted into these model atmospheres, and the evolution of a nuclear winter has been predicted. The sources of soot in a nuclear war are defined by the available weapons and targets. These are concentrated in the United States, Western Europe, and the Soviet Union. The possible scenarios for a nuclear war have been argued endlessly and, of course, will never be settled to the satisfaction of all strategists. For the simulated nuclear winters, several scenarios have been fabricated (all on paper, with minimum damage to the participants).

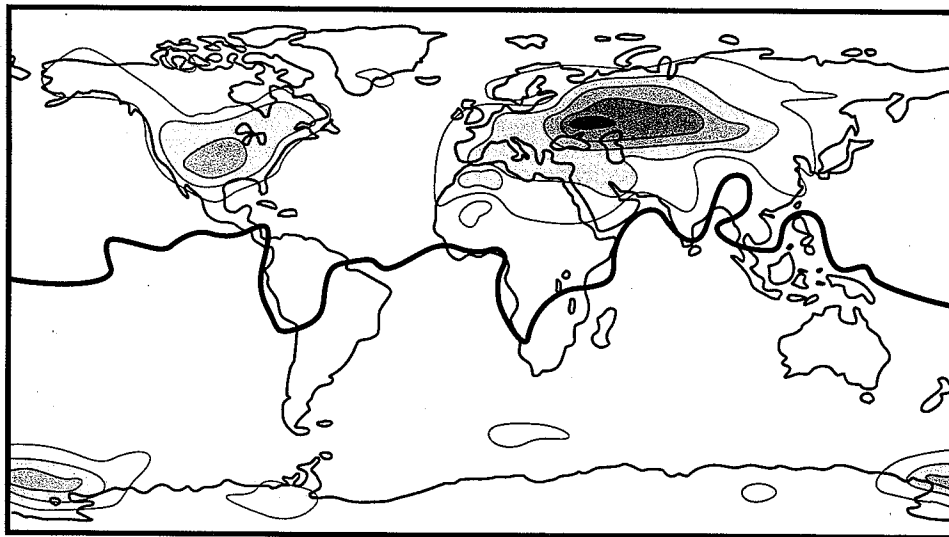
The changes in surface temperatures predicted for a typical nuclear-winter scenario are given in Figure 14.3. The continental interiors beneath the nuclear-generated smoke clouds would become very cold.

The coastal regions and islands, however, would be relatively immune to the cold (if not the dark), as these areas are warmed by nearby ocean heat reservoirs. The normally mild climates of western coastal zones and islands are the result of ocean warmth carried by winds. Hence frigid weather would also be less likely in coastal regions during a nuclear winter. But most other places would be vulnerable to deep cooling.

If the soot were allowed to disperse in the model without absorbing sunlight (that is, as a passive atmospheric tracer), most of the soot particles would be removed by rainout within a few weeks. Regional and global climates would be only slightly affected; a nuclear winter would not grip the land. However, if the soot were allowed to absorb solar radiation (as it really does) and heat up the atmosphere, self-lofting of the heated smoke clouds would result. In the model, soot is rapidly transported from the lower troposphere into the upper troposphere and stratosphere. A widespread temperature inversion forms in the model, suppressing deep convection and precipitation and stabilizing the soot against its removal.

Substantial quantities of smoke can be carried on heated winds from the Northern Hemisphere into

Figure 14.3 Calculated surface cooling caused by the emissions of soot into the troposphere as a result of nuclear war. Patterns are shown for the temperature differences, or anomalies, relative to a "control" calculation without soot emissions. The temperatures are 7-day averages taken 20 days after the start of the "war." Most of the temperature anomalies are caused by strong cooling due to the antigreenhouse effect. The cooling is greatest over large continental land masses, where temperatures may drop by more than 25°C within several weeks. Over the oceans and in coastal regions, the cooling effect is greatly moderated by heat transfer from the oceans. These surface temperature perturbations exceed all known climatic anomalies since the last ice age, more than 10,000 years ago. (Calculations were made by G. Glatzmaier and R. Malone at Los Alamos National Laboratory, 1986)



the Southern Hemisphere stratosphere in a matter of weeks, creating a global-scale climate problem. The putative climatic changes would include rapid land cooling by 10° to 20°C, particularly in the vast agricultural zones of the Northern Hemisphere. The anomalies would be so intense that entire crops would almost certainly be lost almost everywhere. It is likely that losses would also occur in subsequent years. The impact of the projected food shortages would be devastating. One comprehensive assessment predicted up to 3 billion human casualties of hunger and disease during the first year. The future of civilization beyond that point would seem grim, with little infrastructure remaining to support a long-term recovery.

This is global Armageddon rising up to consume a model Earth residing in the memory chip of a computer. This numerical Armageddon, although harmless, teaches valuable lessons about rational restraint in pursuit of peace. Humans, plagued by greed and madness, have contrived smaller versions of Armageddon that also hold lessons concerning the environmental aftermath of warfare.

#### *Kuwait and Saddam's Revenge*

Imagine more than 500 oil wells burning in an area the size of Los Angeles, with turbulent plumes of dark sooty smoke boiling into the atmosphere. Imagine a black sheet of dense smoke filling the sky, turning noon into midnight, nightfall all day long, day after day. Imagine the air thick with petroleum fumes and acrid smoke; imagine a soot fall of black oily particles settling everywhere, staining everything they touch. Imagine the ground dark and desolate under the suffocating pall of smoke, crops withered beneath sunless skies, discolored by soot. Imagine lakes and rivers of shimmering oil soaking the land and fouling the waters. Imagine an oily black rain—like that falling after the atomic bombing of Hiroshima—splattering the landscape and contaminating fodder and soil. This is not a description of hell. It is a picture of Kuwait and other areas of the Middle East in the wake of the Persian Gulf War of 1991. Near the end of that war, Iraqi leader Saddam Hussein unleashed one of the most violent purposeful assaults on the environment in human history.

The events that unfolded in Kuwait had never occurred anywhere else at any other time. Iraqi forces systematically sabotaged some 800 oil wells,

causing fires at about 530 wellheads. Sooty smoke from the oil fires darkened the skies over an area of about 75,000 square kilometers. Land temperatures cooled as much as 15°C below normal. Reports from as far away as Turkey and Afghanistan described greasy “black rain” falling over large areas. Added to this misery was the largest oil spill ever (perhaps 10 million barrels of crude oil sloshing in the northern Persian Gulf).

The Kuwaiti disaster was certainly a horrific demonstration of the misuse of technology against humanity and the environment. It could have been worse. As it turned out, the oil fountains at wellheads burned very efficiently, generating less than one-tenth of the soot that might have occurred under other circumstances. The oil was also contaminated with brine, which left the soot particles coated with salt and ready to be washed out by the first rainfall. If more soot had been generated and if it had been in its usual state of high resistance to washout, the black clouds could have spread much farther. The soot might have affected the Asian monsoons and might have led to climatic anomalies similar to those following large volcanic eruptions (Section 11.6.4). Compared with a putative nuclear winter, however, the Kuwaiti fires and soot clouds were small potatoes. The world can be thankful for that.

#### 14.2.2 CARBON DIOXIDE

The anthropogenic gas that contributes most to global climate warming is carbon dioxide, which is generated by fossil-fuel combustion. It is perhaps ironic that the fuel that drove the engines of the Industrial Revolution also fueled the degradation of the global environment. The science of global warming is described in detail in Chapters 11 and 12, and so there is no need to cover this ground again. But we offer a few comments in reference to technological traps.

#### *Exhaust from the “Engine” of Industrialization*

Most of the conveniences enjoyed by modern society were derived from massive investments in energy production. Early civilization benefited from the discovery of coal as a cheap and efficient fuel for heating and cooking. Later, coal was used to produce steam to drive various mechanical devices and eventually electric generators. Free-flowing oil proved to

be a boon to industry near the turn of the century. Oil refined into gasoline led to a boom in transportation. Coal and oil also proved to be a bane to the environment. Smog and spills have caused havoc with local environments. These regrettable side effects have been manageable in some cases; in other instances, smog and oil slicks were the price paid for power. In time, more and more "essential" uses were found for fossil-fuel energy and the products that can be made from these materials, including fabrics and plastic.

Civilization and its citizens have become completely dependent on fossil energy sources, like junkies on heroin. That would be fine if the sources of the drug were unlimited, and the side effects of using it were minor. Neither condition holds. Even though the supplies of oil and coal are vast, the accessible reservoirs will probably be depleted during the twenty-first century. Even before that, the recovery and refining of fossil-fuel reserves will grow much more expensive as the depth and quality of the fuels drop over time. Yet civilization is hooked on the stuff.

Early industrialists who profited from coal and oil use never questioned its value to society. Despite serious air and water pollution—deemed acceptable as a trade-off for modern products and conveniences—fossil-fuel exploitation raced ahead at full speed. There was no suspicion of global-scale effects. If scientists had stepped forward at the time warning of possible uncertain effects on the Earth's future climate, industry would have brushed them off as alarmists. Svante Arrhenius's early ideas concerning carbon dioxide and climate were not immediately connected with the need to control fossil fuels. No one really wanted to see a potential problem with such a large cash cow.

Should the producers and users of fossil fuels have been responsible for recognizing obvious threats to the climate? Would they have modified their activities in the face of enormous losses of profits, even if they had been convinced that a change in climate was likely? Past experience with industry and business suggests that it would be naive to assume even modestly beneficent acts on their part. Rather, the task of enforcing environmental standards falls on the shoulders of ordinary citizens and civil servants. Although the mess with air pollution and carbon dioxide is, to a degree, the result of individual self-interests, the information necessary to make conservative decisions to protect the long-term quality of life was never made

available to the public. Time and again in history, critical information denied common awareness—intentionally by those who profited from public ignorance—has resulted in long-term environmental tragedy. In the case of fossil fuels, the future hazards may be monumental indeed, although the actual effects remain uncertain (Section 12.4.4).

### *The Benefits of Air Pollution*

In the case of fossil-fuel consumption and the smog that accompanies it, a silver lining has been found—in fact, two silver linings. Smog, it turns out, can absorb ultraviolet radiation and it can cool the greenhouse warming. It is somewhat ironic that the ozone in smog may limit the ultraviolet radiation leaking through a damaged ozone shield. Over the past two decades, as stratospheric ozone has declined a few percentage points on average over the globe, ultraviolet radiation at the surface has not increased in response. In some cases, measurements of ultraviolet radiation in urban regions indicate lower intensities. The moderation of the UV light is related to the ozone and other absorbing components of smog. Paradoxically, the air that chokes us also shades us from irradiation.

Is it a reasonable compromise to suffer bad air quality in order to avoid harmful ultraviolet rays? Hardly. A quick reading of Chapters 6 and 7 should convince anyone even slightly concerned with his or her health that smog must be eliminated, or at least be minimized. The point is that smog needs to be reduced, *and* the ozone layer needs to be protected. There can be no compromise on either issue. The idea that these problems offset each other—no harm, no foul—is nonsense. Indeed, reductions in stratospheric ozone can intensify smog. The increased flux of ultraviolet radiation accelerates smog reactions, cooking up more ozone near the ground. The problems of smog and stratospheric ozone reduction are connected. Both problems must be corrected, not encouraged.

It has recently been discovered that the particulates generated by sulfur dioxide emissions and biomass burning reflect sunlight and lower the temperature of the Earth (the so-called albedo effect [Section 11.6.5]). Thus sulfate aerosols and vegetation smoke particles are effective scattering agents that reduce the amount of solar energy absorbed by the planet (Section 14.3.2). This compensating property of fossil-fuel combustion (in other words, the cooling

effect of the particulates generated, which offsets the warming effect of the carbon dioxide emissions) represents a treacherous sleight of hand. The combustion-generated aerosols are present as long as the fuels are burned; when the burning stops, the aerosols disappear in a matter of weeks. Carbon dioxide, on the other hand, remains in the atmosphere for hundreds of years (Sections 10.2.4 and 12.2). The warming potential of the  $\text{CO}_2$  is masked as it becomes more concentrated. The warning signals of climate change are suppressed. Action to correct the problem is delayed. Eventually, when the fuels run out, the cooling effect of the aerosols will disappear, and the warming effect of the carbon dioxide may appear full blown.

The intricate relationships among the physical, chemical, and biological effects of large-scale technology are not widely appreciated by most lay people, policymakers, or scientists. Scientists may overlook the connections because of their natural academic tendency toward narrow specialization. Most physical scientists, for example, are not familiar with biological principles, and vice versa. But technology sets traps between academic disciplines. There is no easy solution to this contrivance of intellect to focus on details rather than to view the "big picture." Some ideas about protecting the environment, society, and civilization from technological harassment are addressed in Section 14.4.

### 14.2.3 CHLOROFLUOROCARBONS

The environmental controversies involving chlorofluorocarbons (CFCs) are discussed at length in Chapter 13, in Section 12.3.3, and elsewhere in this book. The concentration of CFCs is a perfect paradigm for the pitfalls of new technologies, particularly those compounds intended for widespread use: Beware the wolf in sheep's clothing.

#### *"Miracle" Compounds*

Like so many "miracle" compounds, the chlorofluorocarbons had to be invented. Automobiles and refrigerators and television sets are not mined from the ground or harvested like fruit from trees. They must be manufactured from natural raw materials. Moreover, design and fabrication schemes must be worked out before any can be made. CFCs, it turns out, are much simpler than the refrigerators and air

conditioners they are used in. They are by no means harmless, however.

Chlorofluorocarbons were invented in the early 1930s as a safe replacement for common refrigerants of that time, including toxic ammonia gas. The CFCs have superior properties as a coolant in air conditioners as well. They are non-toxic and can be breathed without harm. Hence CFCs can also be used as a propellant for underarm deodorants, hair sprays, and other compounds used in personal hygiene. Further, CFCs are so inert chemically that they can be used in a variety of industrial processes that require a nonreactive buffer gas. For example, plastic and rubber foams can be blown using CFCs. Finally, because they are relatively cheap and easy to make, the common CFCs have been widely adopted for every possible use.

#### *Environmental Hangover*

The environmental problems that eventually surfaced from the widespread use of the miracle CFC compounds are now legendary. The depletion of the ozone layer (Section 13.5) and greenhouse warming (Section 12.3) are the two main global environmental issues of this century. Like a drunk on the morning after a binge, we are still woozy from the effects of CFCs. We must give them up, yet we are not sure how we will live without them. Although it is clear that to continue using CFCs would lead to severe damage, we experience the discomfort of withdrawal in the form of roll-on deodorants and higher prices for cars. Some damage has already been done to the vital environmental "organs" of the Earth. Signs of cirrhosis of the ozone layer have appeared, although it has not yet failed as a vital filter of toxic rays. The planetary temperature has risen, but the world has not become feverish yet. Unfortunately, the symptoms will persist well into the twenty-first century. So far, just a mild hangover, not delirium tremens. Just a legacy of stress and cancer for the next five or more generations.

### 14.3 Technological Cures

Technology has caused many of today's most serious environmental problems, and the countryside is strewn with technological traps that may snap shut at any moment. Can technology provide solutions as well? It makes sense. If ozone depletion causes

skin cancer, medical techniques can be developed to remove the cancerous lesions produced by excess ultraviolet radiation. If global warming causes the sea level to rise, levees can be built using modern engineering techniques. If nuclear weapons are proliferating around the world, a defensive shield can be constructed in space to ensure national security. Are these ideas feasible? What other technological patches might be worth pursuing? Is there a planetary prophylactic to protect against environmental degradation?

### 14.3.1 PREVENTING ARMAGEDDON

Ever since the first nuclear device was exploded, alarm bells have been ringing. The scientists who invented nuclear weapons immediately realized the jeopardy in which civilization had been placed. Most of the scientists began to lobby against the production and deployment of weapons of mass destruction. Later, after those pleas had been ignored and huge arsenals had been collected, they worked for disarmament and the abolition of nuclear weapons. A few of the inventors took another tack. Rather than dismantle the nuclear systems coveted by a superpower, they thought it might be possible to build other systems that would make such weapons "impotent and obsolete." Enter the Strategic Defense Initiative (SDI).

#### *Star Wars*

If there ever was a bankrupt technological concept, "Star Wars" is it. The idea is to place a shield in space to stop enemy missile attacks using satellite-based weapons. The technological problems of constructing a reliable system to operate for decades in a space environment and to perform flawlessly the first and only time it is ever used are now agreed to be insurmountable. Indeed, such a system could never be tested properly. More to the point, the proposed weapons technologies either would not work or would be vulnerable themselves. Despite early optimism and a few shady promises by proponents, lasers that could fire X-ray beams at enemy warheads have been shown to defy the laws of physics. A backup concept—chemical lasers the size of small ships drifting through space—is less than impractical; it is ludicrous. And "brilliant pebbles," small high-speed "guided bullets," are not much better than BB guns

against a concerted missile attack. Petulant technologists have shrugged off criticisms of the proposed high-tech devices, fibbed to presidents, and wasted enormous resources to pursue this phony concept.

By 1993, the total price tag for Star Wars was about \$30 *billion*! The project is continuing, and the costs are accruing. For that money—roughly \$100 for every U.S. citizen so far—there is not a single useful product to show, let alone a "shield." The money has been wasted in an orgy of spending on oversold and overvalued technology.

In the original Star Wars concept, the United States would be preserved intact in an all-out nuclear war with the Soviet Union, by destroying Soviet missiles and warheads in flight. That goal, embraced by a misinformed president as a moral alternative to mutually assured destruction (MAD), was, if not mad, at least a little loony in the face of 10,000 Soviet warheads. Sights were lowered to preserving enough of the U.S. economy so that the country could prevail over the Soviet Union in the aftermath of a nuclear war. Somalia would likely have more economic and military viability than the United States after an all-out nuclear attack. When the Soviet bloc finally crumbled in the late 1980s, the Star Wars objective was further reduced to the protection of U.S. cities from nuclear attack by Third World powers such as Libya and Iraq. Imagine long-range nuclear missiles launched by Libya at the United States! More logically, a small nuclear bomb would be smuggled into the country and detonated. Behind all the smoke screens and lame excuses, tens of billions of dollars have been wasted on Star Wars.

During the Persian Gulf War, the Iraqis launched a number of Scud missiles at various targets. On the defense, U.S. Patriot missiles scored several hits, although apparently many misses as well. Star Wars advocates took this spotty record as "proof" of the "defensive shield" concept. Woe to us. Tens of billions more dollars will likely be spent to fend off the Scuds that will never come.

The Star Wars fiasco is a prime example of the manipulation of facts, use of secrecy, and lobbying and special interests applied to subvert the best interests of society and, ultimately, the global environment. Money wasted on such technological nonsense enervates the economy (there are few useful "spin-offs" from weapons research) and skews the priorities of governments.

### *Meteor Defense*

The advocates of Star Wars have a new mission: To prevent Earth from being destroyed by a large meteor. There is compelling evidence that a 10-kilometer-diameter meteor collided with the Earth 65 million years ago, wiping out the dinosaurs and most other species of that epoch (Section 4.3.2). The agent of extinction probably involved major climate disturbances triggered by the explosive impact, worldwide dust clouds, global fires, and searing acid rain (Section 11.7.2). Even a much smaller meteor impact could wreak havoc on human civilization. The frequency of meteor impacts (that is, the number occurring in any fixed time interval) increases as the meteor size decreases. Small meteor impacts hit the Earth more frequently than large ones do. An object (a comet or asteroid) the size of the meteor that killed the dinosaurs hits the Earth only once every 30 million years. However, an object the size of a football field may hit every 10,000 years.

The Tunguska meteor exploded over a remote area of Siberia on the morning of June 30, 1908. The detonation flattened 2000 square kilometers of dense forest, blowing full-grown trees over like matchsticks. The closest observer, 60 kilometers away, was blown off his feet. If the Tunguska meteor had fallen over New York City, the casualties would have numbered in the hundreds of thousands, and Manhattan would have been leveled. Such an event happens every few hundred years. Whenever a comet enters the solar system on its way around the sun, it might be deflected by Jupiter or Saturn onto a collision course with Earth. Although comets will pass within several hundred thousand miles of the Earth in the next century, it is highly unlikely that one will actually strike the surface. Fortunately, near misses do not count.

Nevertheless, Star Wars proponents have scared up their own bogeyman—meteors. They point out that the collision of a meteor with Earth is inevitable. Indeed it is. They mention that even a small hit on a city would be devastating. Indeed it would be. They note that a bigger impact could change the climate and create a “meteorite winter,” leading to agricultural failure and worldwide famine. Shades of nuclear winter. What they fail to underscore, however, is that the probability of an event of any consequence happening during the next few centuries is vanishingly small.

Despite incredible improbability, the deployment of a space- or moon-based nuclear-tipped meteor-

terminator is recommended. Carrying a warhead of up to 1 million megatons of nuclear explosive power, the terminator would sit and wait for an invading asteroid or comet.<sup>4</sup> At the right moment, perhaps centuries in the future, this supermissile would be launched to pulverize the interloper. On Earth, we would hope and pray that the guidance system had remained sound. The tens or hundreds of billions of dollars would have been well spent.

A few years ago, a cold war was conjured up to justify obscene expenditures of public funds to build useless weapon systems that now must be dismantled at additional great cost. Today, a cold rock is cast as the enemy in another fuzzy scheme to spend tax revenues. The next thing you know, the civil defense advocates of the past will reappear urging everyone to build a personal meteor shelter.

### **14.3.2 COOLING DOWN THE GREENHOUSE**

The threat of global changes in climate associated with greenhouse warming has fostered a cottage industry in technological cures. After all, a practical scheme could forestall the climatic chaos that may follow warming *and* likely turn a handsome profit for the inventor of the scheme. This potent wedding of philanthropy and profit has spawned a slew of climate-sensitized entrepreneurs and technologists. The basic physical, chemical, and biological principles that allow such schemes to blossom are described in other sections of this book. We discuss next some creative applications of these principles (also see the summary of some current ideas in Section 12.5.3).

#### *Fortifying an Anemic Ocean*

The oceans represent the largest reservoir of carbon dioxide that humans have access to in a relatively short time. (In Sections 10.2.4 and 12.2.3, the global cycle of carbon dioxide is described in detail.) The oceans naturally absorb excess carbon dioxide from the atmosphere, but this process takes hundreds of years to occur. Why not speed it up? Indeed, if “carbon burial” in the oceans could be accelerated,

4. The largest nuclear device ever detonated was equivalent in explosive power to about 60 million tons (60 megatons [MT]) of TNT. In principle, there is no limit to the size of an explosive device based on nuclear fusion. The trigger for such a device would be a series of nuclear fission explosions the size of the atomic bomb dropped on Hiroshima.

the need to curtail CO<sub>2</sub> emissions would disappear. Normally, living organisms in the oceans constitute a "carbon pump." They incorporate carbon into their bodies, and when they die, the carbon sinks to the bottom with them.

The carbon uptake in the oceans begins when carbon dioxide dissolves in the ocean water to form carbonate compounds (Section 10.2.4. Equations 10.22, 10.23, and 10.31). Microscopic plants (phytoplankton) in the oceans absorb the dissolved CO<sub>2</sub>, much as terrestrial plants absorb CO<sub>2</sub> from the air. Through photosynthesis, this carbon dioxide is converted to organic matter (Section 4.2.3). The phytoplankton are then eaten by zooplankton, which are eaten by larger organisms, eventually leading to food for whales. The marine food chain is anchored by phytoplankton. When the larger organisms die or defecate, organic "detritus" is generated. The detritus can be eaten by bacteria and recycled as carbon dioxide, much as organic debris is recycled on land. Otherwise, the carbon-rich material settles into the deep oceans, from which it will not return for centuries.

The biological productivity of the surface oceans is generally limited by the availability of trace nutrients, especially fixed nitrogen, phosphate, and iron. There is plenty of carbon dioxide, sunlight, and water, of course, to carry out photosynthesis. Plant growth in particular is restricted by deficits in nutrients (the limiting factor for zooplankton and other aerobic feeders is oxygen, whereas bacteria usually consume everything in sight under most conditions). Nutrients are absorbed in fixed ratios compared with carbon; these fixed proportions are called the **Redfield ratios**. The Redfield ratio of fixed-nitrogen (N) to carbon (C) atoms, for example, is about N/C = 1/7. This is roughly the elemental ratio of nitrogen to carbon found in living organisms and the amino acids from which they are built.

Different areas of the world oceans exhibit deficits in different key nutrients. In the southern Pacific Ocean near Antarctica (the Southern Ocean), the waters are relatively poor in iron but rich in other nutrients. The Southern Ocean is, however, a region where cold water is sinking to form abyssal "bottom water." Carbon brought down there is carbon removed for a long time.

A clever marine scientist recognized the possibility of burying carbon in the Southern Ocean if it were fertilized with iron. The phytoplankton in this area are limited in productivity mainly by a lack of iron.

That is, the waters are anemic. Iron could be added in a soluble form using ships or aircraft to spread it over a sea area of several million square kilometers.<sup>5</sup> One soluble iron compound, ferric chloride, is cheap and plentiful. About 1 million tonnes of iron per year would be needed to remove 1 gigatonne (1 billion tonnes) of carbon. The Redfield ratio for iron (Fe) to carbon (C) is about Fe/C = 1/1000. Hence, the amount of carbon removed is just the amount of iron spread over the water divided by the Redfield ratio for iron. This estimate assumes that all the iron is eventually tied up in biomass that sinks into the deep ocean.

Ships laden with iron would ply the southern Pacific Ocean spraying iron and deep-sinking carbon dioxide. The idea is simple and elegant. It uses basic biological, physical, and chemical concepts. Forget the thousand ships laden with iron, vast ocean tracts unnaturally fertilized, billions of dollars spent. The solution, although large on an engineering scale, is approachable. Unfortunately, it would probably not work. Oceanographers carrying out detailed simulations of the carbon cycle under the conditions existing in the Southern Ocean have tentatively concluded that most of the carbon would not sink, but would be recycled by mixing before it could be "buried." The potential removal of carbon dioxide by this method might amount to one-tenth the total present-day source from fossil fuels. That is enough to make a dent, but only a dent.

One group of Japanese researchers has proposed another method for burying carbon dioxide in the oceans. The CO<sub>2</sub> would be compressed into a liquid and pumped to the ocean bottom. Being denser than seawater, the liquified carbon dioxide would stay put. Moreover, the overlying pressure of the water would keep the CO<sub>2</sub> from vaporizing and rising as effervescence. So far, no carbon dioxide has been sunk this way. A proposal similar in concept to those just mentioned uses wood as the carbon vehicle. The trees would be grown, the logs would be harvested, and the wood would be buried in an environment where decay was very slow. To keep up with the output of carbon dioxide, several million square

5. Iron cannot be dumped into the ocean in its pure metallic state. Nails would sink immediately. In order to be useful to living organisms, the iron must be transformed into a soluble species of ferric or ferrous iron. Iron exposed to air and water rusts, producing these soluble forms. Metal buried in soil eventually decomposes by rusting and is mineralized. Rusting takes time, however. The decomposition process can be accelerated with acids, and the iron crystallized for convenient application.



kilometers of forest would have to be under continuous cultivation and cutting for a century or more. It could be done, of course, but it would pose extreme new problems. Perhaps a better solution is to allow the carbon dioxide to accumulate and compensate for its effect on the climate.

#### *Smoke and Mirrors: The Albedo Effect*

The basic planetary energy balance, which determines the global climate over long time scales, is outlined in Chapter 11. One of the key factors controlling the energy balance is the albedo, or reflectivity of the Earth. The albedo, in turn, is controlled by a number of parameters, including the conditions of the land surface, the cloudiness of the sky, and the amount of smoke in the air. (Specific relationships between the albedo and climate are described in Sections 11.6.4 and 11.6.5; see also Section 3.2.2.) In particular, the albedo can be affected by changes in the particulate loading of the atmosphere. The more particulates that are present, the hazier the air and generally the more reflective the atmosphere will be. The albedo would be reduced only in the circumstance that highly absorbing particles, like soot, were present in large amounts.

There is a substantial body of evidence illustrating the effect of a change in albedo on climate, caused by volcanic eruptions. The eruption of Mount Tambora (Indonesia) in 1815 provides the most spectacular example of the potential climatic impact of volcanic eruptions in historical times (Section 11.6.4). Nonetheless, the Tambora event is not well documented because the event was quite remote and the geophysical data collected at the time were quite crude.

Relatively small volcanic eruptions, such as Mount St. Helens (which exploded in Washington State in 1980), do not cause global effects. In the case of St. Helens, a plume of ash spread over the western United States, but did not go much farther. On the other hand, larger recent eruptions, such as El Chichón (Mexico) in 1982 and Mount Pinatubo (Philippines) in 1991, have had a major global impact. Both Pinatubo and El Chichón emitted a large amount of sulfur dioxide, along with ash and other debris. Sulfur dioxide that is injected into the stratosphere is converted to sulfuric acid aerosols (Section 3.3.4), and these spread over the entire globe, causing spectacular purple twilights (Section

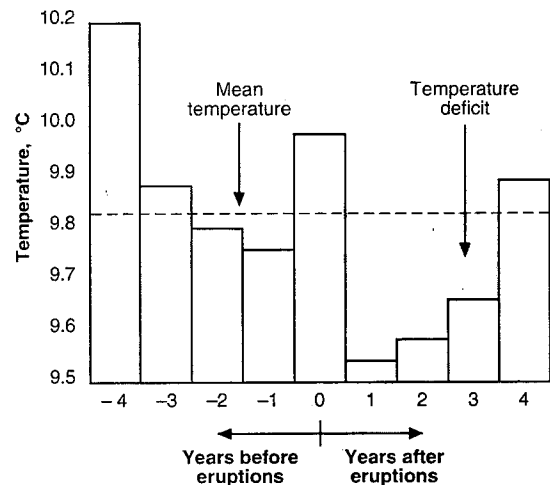


Figure 14.4 Global average temperatures before and after seven major historical volcanic eruptions (1815, 1822, 1831, 1835, 1846, 1902, and 1963). The number of years before (negative) or after (positive) the year an eruption occurred is indicated. The global temperature averaged over all seven eruptions is shown for each year in the relative chronology. There is, on average, an apparent temperature deficit of several tenths of a degree Celsius during a span of 1 to 3 years following such eruptions. (Data from S. Schneider and C. Mass, "Volcanic Dust, Sunspots, and Temperature Trends," *Science* 190 [1975]: 741)

3.2.3). In addition, less sunlight reaches the Earth's surface, and the climate cools slightly. Although the extent of cooling is uncertain, a global average temperature decrease of 0.5°C is expected the year following a major volcanic eruption. The volcanic aerosols disappear from the stratosphere over a period of several years, and the climatic anomaly fades just as quickly.

The effects of notable historical volcanic eruptions on the global temperature are illustrated in Figure 14.4. Variations in the magnitude of the effects caused by volcanic eruptions can be attributed to differences in the materials emitted by each volcano, the height of the volcanic injections, and the latitude of an eruption. If the eruption plume extends into the stratosphere, for example, the sulfuric acid aerosols that are formed can persist long enough to disperse over a large area of the globe. The stratosphere is dynamically stable, like a large temperature inversion (Section 2.3.3). Storm clouds do not penetrate from weather systems in the troposphere below. Rain and snow do not form there. Hence the removal rate of volcanic debris from the stratosphere is quite slow. Small particles have a

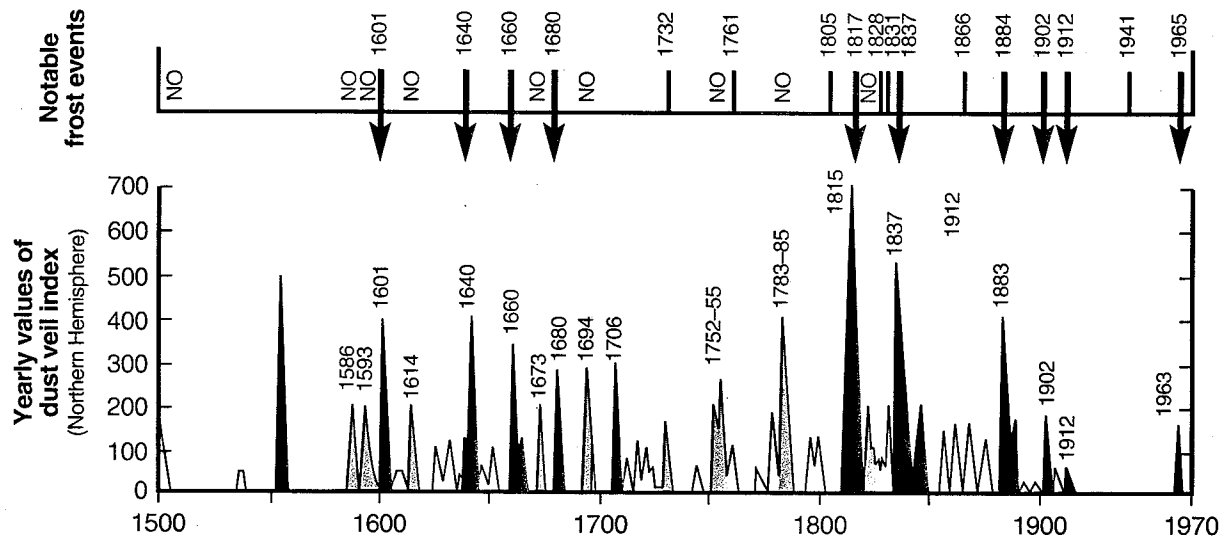


Figure 14.5 The record of frost damage in bristlecone pine trees in the southwestern United States, correlated with major volcanic eruptions. The upper panel identifies the years in which frost damage is evident in tree ring growth. Arrows indicate those years when a major volcanic "dust veil" also existed in the Northern Hemisphere, as suggested by the optical data summarized in the lower panel in the estimated "dust veil index" (DVI). The DVI roughly corresponds to the optical depth of the volcanic aerosol layer in the stratosphere. Years of unseasonable frost damage (upper panel) are indicated without arrows if no substantial dust veil was noted (lower panel). The symbol NO in the upper panel indicates a year in which a notable dust veil appeared, but not frost damage. Volcanic events corresponding to years with frost damage are shown as solid-filled peaks in the lower panel. Other major dust veil events are shown as gray-filled peaks. (Data from V. LaMarche and K. Hirschboeck, "Frost Rings in Trees as Records of Major Volcanic Eruptions," *Nature* 307 [1984]: 121)

residence time of one to several years. That is long enough to allow a solar-energy deficit to build up, but not long enough to cause a long-term climate anomaly.

The fact that volcanoes can change the climate is supported in a number of geologic, biological, and historical records. In one particularly important set of data, damage to tree rings indicates years with extreme weather and climate anomalies. Figure 14.5 gives the record of frost damage to the ancient bristlecone pines of the southwestern United States. The striking point of this study and of many other data is that climate can be manipulated relatively easily within certain small bounds. The short-term climatic variability associated with volcanic eruptions, the El Niño phenomenon in the equatorial Pacific Ocean (Section 12.4.2), and solar variability (Section 11.6.2) all demonstrate that tweaking the climate system is possible. The magnitude of the average year-to-year temperature changes for natural perturbations is small—1 degree or less—but the fact of a climatic response to specific forcing is clear.

Climate forcing associated with changes in solar-energy input, caused by variations in the sun's brightness or the reflectivity of the Earth, have similar climatic implications. Both kinds of phenomena can be studied using the energy balance box model of Section 11.3.2. Indeed, the effect of a change in the planetary albedo on average surface temperatures over a long time period can be estimated using the simple climate Equation 11.14. This relationship can be rewritten in a form suitable for calculating small temperature changes from the norm (the "climate-change" equation):

$$\frac{\Delta T_s}{T_s} = -\frac{1}{4} \frac{\Delta \alpha_e}{(1 - \alpha_e)} \equiv -\frac{\Delta \alpha_e}{3} \quad (14.1)$$

Here, the normal surface temperature,  $T_s$ , decreases ( $\Delta T_s < 0$ ) as the albedo,  $\alpha_e$ , increases ( $\Delta \alpha_e > 0$ ). Since the average surface temperature is close to 300 kelvin, Equation 14.1 can also be expressed approximately as

$$\Delta T_s \approx -100 \times \Delta \alpha_e \quad (14.2)$$

Hence a change in the average planetary albedo of 0.01 (from the current albedo of about 0.33, that is, a 3 percent change in the albedo) can lead to a surface temperature change of about 1°C.

If the albedo increases, the surface will cool. If the albedo decreases, the surface will warm. In either case, the shift toward a new climatic state would take decades or longer to evolve, because the ocean heat reservoir would take a long time to equilibrate (Section 11.5). The greenhouse effect and any internal adjustments in the climate system could further modify this result. Nevertheless, Equations 14.1 and 14.2 are useful for making first-order estimates of global climate changes related to long-term variations in the albedo.

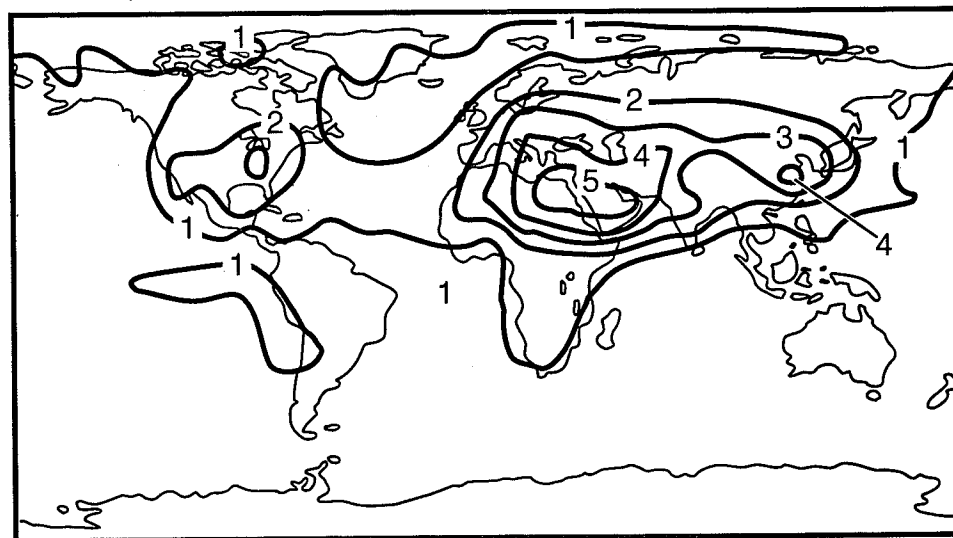
Several possible schemes for intentionally altering the albedo of the Earth are described next. In the particular cases we use, our goal is to cool the planet to compensate for an increase in the abundances of carbon dioxide and other greenhouse gases. Neither the details of the climatic response on regional scales nor the evolution of the response over time is considered in any depth. Instead, the objective is to create artificially a first-order compensating effect for the projected global warming of several degrees Celsius associated with greenhouse gases. The fact that much is being neglected should immediately raise a warning flag.

### *The Sulfate Shield*

The ozone shield protects the Earth from harmful solar ultraviolet radiation. It happens that a "sulfate shield" also exists that may protect the Earth from climate warming. Unfortunately, it is an inefficient prophylactic. The sulfate shield actually consists of the aerosols in the lower atmosphere. In Section 14.1, one source of these aerosols—dimethyl sulfide (DMS)—was discussed in the context of a natural climate feedback system. Another component of the sulfate shield consists of the aerosols generated in polluted air. Our old nemesis, polluted haze (Section 6.5), may be acting as a climate "thermostat" to limit greenhouse warming. The sulfate particles originate as sulfur dioxide emitted mainly during the combustion of fossil fuels, which are the primary source of atmospheric sulfur, equaling or surpassing most natural sources (Sections 9.3.2 and 10.2.1). The sulfur emissions undergo chemical conversion to sulfates and end up on haze particles or in acid rain.

Figure 14.6 shows the geographical distribution of sulfate aerosol effects. The sulfate aerosol, which is dominated by the human consumption of fossil fuels, is concentrated in the northern midlatitudes. Unlike those in the stratosphere, aerosols in the troposphere have a relatively short residence time in

Figure 14.6 The distribution of sulfate aerosols in the lower atmosphere. The contours provide a relative estimate of the climatic forcing effect of the particles, the effect being greatest where the aerosols are denser. Most of the sulfate effect is due to anthropogenic emissions of sulfur dioxide over the Northern Hemisphere's continental landmasses, particularly at middle latitudes. (Data from R. Charlson, J. Lovelock, M. Andreae, and S. Warren, "Perturbation of the Northern Hemisphere Radiative Balance by Backscattering from Anthropogenic Sulfate Aerosols," *Nature* 326 [1991]: 655)



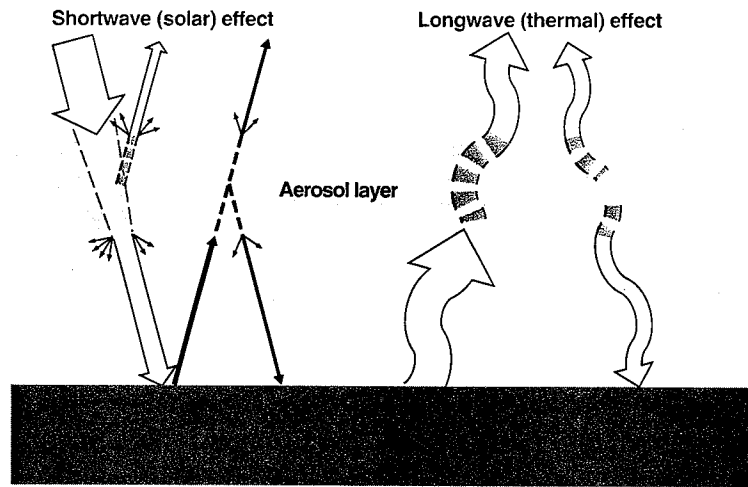


Figure 14.7 The effects of a layer of sulfate aerosols located in the stratosphere on the fluxes of solar (shortwave) and thermal (longwave) radiation. Sunlight is affected mainly by aerosol scattering, which increases the reflected component, thus enhancing the albedo and reducing solar insolation. Thermal radiation is affected primarily by radiation, warms the stratosphere somewhat, and strengthens the greenhouse effect. The effect on solar radiation is typically much larger than the effect on infrared radiation.

air. Indeed, these aerosols near the surface are depleted in a matter of hours or days. The aerosols formed over the eastern United States travel over the North Atlantic Ocean, but rarely make it as far as Europe. Similarly, the concentrations of sulfate aerosols over southern Europe and eastern Asia reflect the local sources of sulfur emissions in those areas. Recall that these pollution particles are thought to provide a “benefit” in reducing ultraviolet radiation at the surface and cooling the planetary greenhouse effect (Section 14.2.2).

The tropospheric aerosols reduce global temperatures in two ways.

1. The aerosols directly reflect sunlight and enhance the planetary albedo.
2. The pollution particles, like those generated from dimethyl sulfide (Section 14.1), cause clouds to become more reflective, further enhancing the albedo.

Both these tendencies to increase the albedo are fairly weak, however, owing to the difficulty in altering cloud reflectance.

The fact that tropospheric aerosols are short lived means that they would be less useful as climate moderators in environmental engineering schemes. To produce a compensating albedo effect on greenhouse warming, huge amounts of sulfur would have to be released into the atmosphere, as much as

several hundred million tonnes per year. Such actions, filling the air with respirable sulfate particles (Section 7.1.2), would not be viewed as a general benefit to human health. And the impact on visibility would be devastating.

#### *The 3 Percent Solution*

The role of stratospheric aerosols in controlling the global radiation balance and climate is depicted in Figure 14.7. It happens that the sulfate particles have a much stronger effect on visible radiation (at short wavelengths) than on infrared radiation (at long wavelengths). This allows the aerosol layer to cool the surface, because of two effects.

1. Less warming sunlight reaches the surface.
2. The thermal longwave radiation emitted by the surface in the “atmospheric window” spectral region (Section 11.4) is not efficiently trapped to enhance the greenhouse effect.

The net effect, therefore, of adding sulfate aerosols (or any other small scattering particles) in the stratosphere is to cool the surface, similar to the antigreenhouse effect of smoke described in Section 14.2.1 in relation to nuclear winter.

Figure 14.8 shows the cooling effect of stratospheric sulfate aerosols. The aerosols are defined in

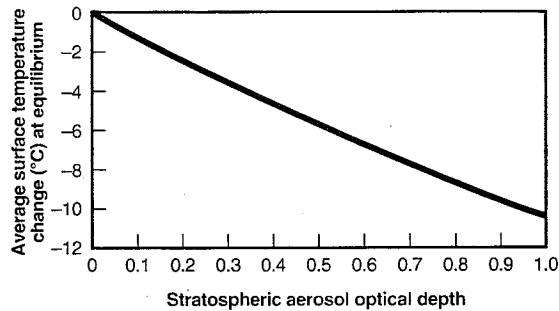


Figure 14.8 The surface cooling effect of a layer of stratospheric sulfate aerosols. The aerosol optical properties are defined in terms of the optical depth of the layer for sunlight in the middle of the visible spectrum (at a wavelength of 0.55 micron). The surface temperature decreases correspond to the new equilibrium condition, or steady state, of the climate system after fully adjusting to the modified radiation forcing. The new equilibrium state is not reached for a decade or longer, owing to the thermal inertia of the oceans. (Data from J. Pollack, O. Toon, C. Sagan, A. Summers, B. Baldwin, and W. Van Camp, *Journal of Geophysical Research* 81 [1976]: 1071)

terms of the optical thickness of the particulate layer. (See Section 3.2.3 for a definition of “optical thickness,” or “optical depth.”) The scattering efficiency of the aerosol layer increases as the optical depth increases. The albedo of the aerosol layer and the cooling effect of the aerosols increase with scattering efficiency. Over a relatively wide range of aerosol optical depth, the relationship between the optical depth and surface equilibrium temperature change is quite linear. That is, if the optical depth of the sulfate layer is doubled, the decrease in surface temperature will also double. From Figure 14.8 it is apparent that an optical depth of 0.1 can lead to a surface temperature decrease of about 1.5°C.

The optical depth of an aerosol layer usually specified at a specific wavelength of radiation, say the mid-visible wavelength of 0.55 micron, or 550 nanometers (nm). The optical depth varies with wavelength; typically, the optical depth decreases slowly as the wavelength increases, roughly in an inverse relationship to wavelength. That is, if the wavelength doubles, the optical depth is halved. The potential decrease in surface temperature depends on the wavelength dependence of the optical depth and on the length of time that the aerosol layer is present. If the aerosol properties are fixed over a long period, then the surface temperature change will achieve a new steady state after several decades. This new state

represents the *equilibrium* climate perturbation corresponding to that aerosol layer. If the aerosol properties change over time (that is, if the particle sizes, the optical thickness of the aerosol layer, or other parameters defining the particles vary), then the perturbation in surface temperatures at equilibrium will be affected accordingly. Recall that major volcanic eruptions create optical depths of ~0.1 to 0.2 but that the global surface temperature decreases only about 0.5°C. Volcanic aerosol layers are too short lived to achieve an equilibrium state of maximum surface cooling. That is, the cooling is transient and smaller than the potential cooling effect of a permanent aerosol layer.

How can the stratospheric sulfate layer be thickened? Volcanic eruptions do this naturally by injecting large amounts of sulfur dioxide directly into the stratosphere. Lifting 10 million to 30 million metric tons of sulfur dioxide to stratospheric heights in aircraft each year has been suggested as a means of mimicking volcanic eruptions. This would require something like a thousand jumbo-jet flights every day. The flights would need to continue for as long as the threat of global warming persisted. Since carbon dioxide may linger in the atmosphere for a century or more, an artificial aerosol layer would have to be maintained over that span of time. To be effective, the sulfur dioxide must be dispersed throughout the stratosphere. The aircraft would have to cover most points on the globe, flying at all latitudes in both hemispheres. The aerosols generated in dense sulfur dioxide trails just behind the aircraft would likely be too large for optimal climate modification. Moreover, new planes would need to be designed to fly at much higher altitudes than the present jumbo jets can (up to at least 20 kilometers, compared with a ceiling of about 14 kilometers for existing commercial large-body airframes).

The quantity of aircraft exhaust emitted into the stratosphere itself would be unprecedented. Nitrogen oxides and water vapor from the engines could lead to an unacceptable depletion of ozone through direct chemical attack (Section 13.5.3). Indeed, in the past, stratospheric aircraft fleets have been banned by Congress for just this reason. The threat is particularly serious in the Northern Hemisphere, where corrections for global warming would be sought.

Figure 14.9 depicts an alternative concept to compensate for global warming. The carbon-based fossil fuels that are widely used to generate energy

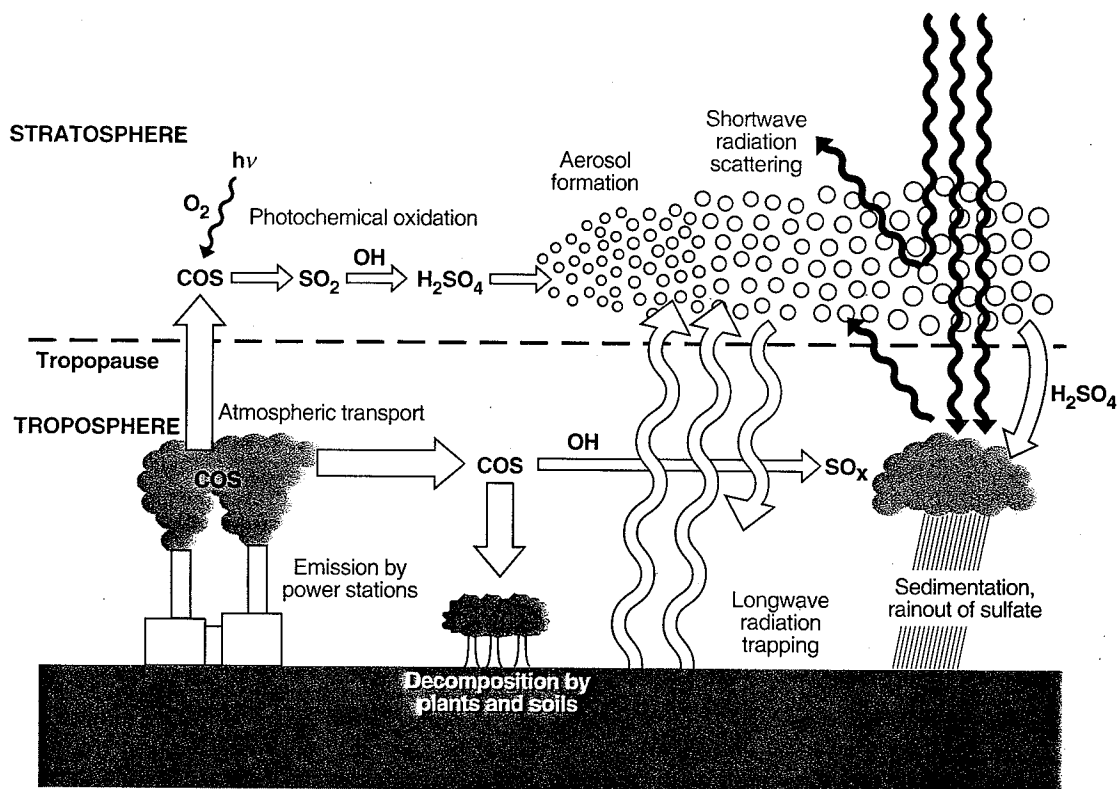


Figure 14.9 A scheme for compensating for the greenhouse-warming effect of carbon dioxide by forming a semipermanent layer of stratospheric sulfate aerosols using the sulfur in fossil fuels. That sulfur, which contributes to local and regional pollution problems, can be converted to carbonyl sulfide (COS) before being emitted into the atmosphere. Carbonyl sulfide is more stable in the atmosphere and, over time, is transported to the stratosphere. There, COS is photochemically transformed into sulfuric acid, which condenses into aerosols that modify the radiation and climate.

and that emit carbon dioxide into the atmosphere as a by-product also contain trace amounts of sulfur. Following combustion, the sulfur is released primarily in the form of sulfur dioxide. On average, fossil fuels contain a small percentage of sulfur by mass. Coal, in general, contains the most sulfur, oil somewhat less, and natural gas the least amount. The sulfur is a nuisance. (Sections 6.1.2 and 7.2.1 [in addition, Sections 7.1.2 and 7.4.4] describe the health hazards of sulfurous smog.) Sulfur emissions also create haze that degrades visibility (Section 6.5). In addition, sulfur emissions create acidic rain in regions of the world where energy production is highly concentrated (Sections 9.3.2 and 9.5.2). To avoid these problems, sulfur is removed from petroleum during processing or is scrubbed from smokestack effluents of power plants. The removal of the sulfur is expensive. The cleanup is forced by the serious nature of the pollution that is generated. If sulfur were removed from

fossil fuels and used to offset greenhouse warming, the multiple benefits to society could be enormous.

That is the concept sketched in Figure 14.9. Carbonyl sulfide (COS) is a common “reduced” form of sulfur. Along with hydrogen sulfide and dimethyl sulfide, carbonyl sulfide is one of the most important sulfur compounds in nature. COS is produced by bacteria in anaerobic environments and can be absorbed by plants. Combustion processes also generate some carbonyl sulfide, and it may be formed as a chemical product when carbon disulfide ( $\text{CS}_2$ ) is photochemically decomposed. Carbonyl sulfide is the most abundant sulfur-bearing gas in the atmosphere, having a relatively uniform mixing ratio of about 0.5 part per billion by volume (ppbv) throughout the lower atmosphere. The lifetime of COS in the atmosphere is uncertain, but appears to be at least 1 year. That is an important property, which allows COS to drift far from its sources before being destroyed.

When COS is emitted at ground level, it can be transported over long distances and may travel between the hemispheres. Because of this dilution, COS does not generate local sulfate haze. Nor does it significantly acidify precipitation on regional scales. In other words, converting the sulfur in fossil fuels to COS largely eliminates the local and regional environmental impacts of the sulfur emissions.

What about the global effects of the COS emissions? The total amount of sulfur emitted by fossil-fuel combustion worldwide approaches 100 million tonnes (Mt) of sulfur annually (Section 9.3.2 and 10.2.1). But after being converted to sulfuric acid (Section 3.3.4), that quantity could only marginally increase the acidity of rainfall around the world. In fact, by spreading around the sulfuric acid, widespread environmental damage is avoided even as regional acidity is mitigated.

Most of the carbonyl sulfide emitted in the troposphere is destroyed there—up to 80 percent. The rest, about 20 percent, is transported into the stratosphere, where it is transformed into stratospheric sulfate aerosol particles. The observed concentration of COS falls off with height above the tropopause, owing to photochemical decomposition at high altitudes. The background stratospheric aerosol layer is a consequence of the sulfur liberated from naturally occurring COS. A fraction of the excess COS generated from fossil fuels would therefore add to the normal aerosol layer.

Nearly 50 million tonnes of sulfur (S) could be converted to COS annually (equivalent to about 100 Mt of COS). The conversion of 20 percent of this COS to stratospheric sulfate aerosols would be equivalent to injecting roughly 20 million tonnes of sulfur dioxide into the stratosphere,<sup>6</sup> like having a major volcanic eruption every year. Because this artificial sulfur injection could be maintained over many years, an equilibrium climate cooling of several degrees Celsius would be expected.

The advantages of the COS scheme can be summarized as follows:

1. The solution already lies in the fossil fuels that are causing the problem. The 3 percent sulfur

6. For each S atom in  $\text{SO}_2$ , there are two O atoms. The mass of S is 32 amu, and the mass of O is 16 amu. Hence each  $\text{SO}_2$  molecule weighs twice as much as an S atom. Ten Mt of S is equivalent to 20 Mt of  $\text{SO}_2$ . For COS, the arithmetic is slightly different. A carbon atom has a weight of 12 amu. A COS molecule therefore weighs  $12 + 16 + 32$  amu = 60 amu, which is slightly less than the 64 amu of  $\text{SO}_2$ .

content of the fuels provides the source of reflective aerosols for mitigating greenhouse warming.

2. The cost of converting fugitive sulfur emissions to COS would be cheap compared with the cost of drastically reducing  $\text{CO}_2$  emissions associated with energy production using fossil fuels.
3. The technology for converting  $\text{SO}_2$  to COS is quite simple, involving basic thermodynamics and catalytic chemistry. Moreover, the economy and society would not be significantly disrupted during the changeover to COS emission.
4. The excess COS would be widely dispersed and diluted by winds around the planet, eliminating most of the local and regional pollution effects, including sulfate haze and acid rain, connected with sulfur emissions from fossil-fuel combustion.
5. The stratospheric aerosol layer would be formed in a natural way, without the need for aircraft flights or other forms of mass intervention. The cooling mechanism would be similar to that following volcanic eruptions.
6. The thickness of the enhanced aerosol layer and its duration over time could be closely controlled by regulating the rate of COS emission.
7. Because sulfur would be removed from fuels, or combustion products, before being emitted into the atmosphere as COS, the sulfur could be retained, thereby improving regional air quality in any case;
8. If the COS emission were halted for any reason, the atmosphere would return to its initial state within a few years (because the atmospheric lifetime of COS is ~1 year).

There seem to be many advantages to this concept. How could it fail? The disadvantages have not been mentioned, and they are not trivial. For one thing, carbonyl sulfide, like most sulfides, is highly toxic. The atmospheric COS would be concentrated by a factor of 100 or more if the climate mitigation scheme were implemented. Concentrations of COS would approach 0.1 part per million by volume (ppmv). Ozone in this amount is considered to be a health hazard. Carbonyl sulfide in this concentration certainly is. Thus, the high concentrations of COS required for mitigation would pose a worldwide health hazard, not just locally but everywhere at all times. Near the COS emission sites, the concentrations could be considerably

larger and therefore more deadly. Moreover, when COS decomposes, it corrodes metals and causes stomatal damage in plants. Adding insult to injury, sulfides like COS have a powerful odor. For example, the smell of rotten eggs is due to hydrogen sulfide ( $\text{H}_2\text{S}$ ). Any system designed to produce COS would generate an overwhelming stink over a large region. As in the case of  $\text{SO}_2$ , COS emissions would need to be diluted by using very high smokestacks, for example, or by mechanically mixing emissions with clean air.

The major problems with massive COS emissions would be related to the aerosols created by the excess sulfur. Indeed, the disadvantages in this regard are common to all solutions that propose creating a stratospheric sulfate aerosol layer to mitigate climate warming. An aerosol layer thick enough to cool the climate by several degrees would cause the skies overhead to be milky white, not blue. This effect is related to the scattering of sunlight by the aerosols and is much like the effect of haze on visibility in smoggy air (Sections 3.2.2 and 6.5.2). No more blue skies, ever, anywhere, just an oppressive global pall of haze. Still, that may be only a minor issue concerning aesthetics.

The stratospheric sulfate aerosols also are implicated in the global depletion of ozone. Such particles have been shown to cause ozone destruction, much like the polar stratospheric clouds responsible for the ozone "hole" (Section 13.7.4; see also Section 14.3.3). After the eruption of Mount Pinatubo in 1991, the total amount of stratospheric ozone worldwide declined by up to 10 percent between 1992 and 1993. That depletion healed as the volcanic aerosols were removed from the stratosphere. In the COS emission scenario, however, the aerosol layer would be semipermanent, being renewed continuously for a century or longer. Thus while the greenhouse effect was being fixed, the ozone layer would be threatened. The ozone degradation would persist as long as the artificial aerosol layer was present.

The sulfate aerosols themselves would scatter and block some of the dangerous ultraviolet radiation leaking through the depleted ozone layer. However, the scattering effect of the aerosols is insufficient to prevent a net enhancement of UV-B radiation at the ground. This situation would not be acceptable without large doses of sunscreen.

The objections to massive COS emission to correct the greenhouse warming effect can be summarized as follows:

- The toxicity of sulfides
- The smell of sulfides
- No more blue skies
- Stratospheric ozone depletion, with ultraviolet spring replacing greenhouse summer

The 3 percent sulfur solution for climate mitigation shows a common outcome encountered in dealing with environmental problems: Even the simplest ideas become increasingly complex the deeper you probe. Even straightforward technologies can generate nasty side effects. Easy or convenient solutions quickly grow into bigger headaches. Specialists with quick answers turn out to be charlatans.

#### *Fourth of July*

The Fourth of July celebration last year: hot dogs, fireworks, rockets bursting in air. Smoke and flares and warm flat beer, a cool summer night awash in the glare. We could be celebrating the Fourth of July all year long if one group of technicians had their way. They propose to turn down the greenhouse warming effects of carbon dioxide by filling the stratosphere with dust. That is not a novel idea, as the previous sections demonstrate. The method of delivering the dust to the stratosphere, however, is rather unusual. It would be lofted using 16-inch artillery shells!

It seems that the navy has a number of large ships equipped with very large guns. The guns fire enormous shells that are usually filled with explosives directed at targets miles away. Most of the time the guns are silent. Why not, it is argued, use those guns to save our way of life? Instead of high explosives, the shells can be filled with dust and a small explosive charge. The propellant would be powerful enough to loft the shells as high as 15 kilometers, into the lower stratosphere. Like microscopic volcanic eruptions, each shell would add a little dust to the stratosphere. Eventually, a dense layer could be built up and maintained by continuous bombardment. We have the artillery; we have the dust. Why not?

For one thing, the global scale of the problem comes into play. To be effective, perhaps 30 million metric tons of dust would need to be injected into the stratosphere every year.<sup>7</sup> Suppose that each artil-

7. Mineral dust would generally be less effective than sulfate aerosols in creating climatic anomalies. For one thing, it is not easy to produce and widely disperse mineral grains with sizes much smaller than 1 micrometer. Small grains tend to stick together, as in a powder, and are difficult to separate. Sulfate aerosols, on the



lery shell could carry and disperse 100 kilograms (about 220 pounds) of fine dust particles. That amounts to roughly 300 million shells fired each year. That amounts to about 10 shots every second of every minute of every day for the next century. If 1000 guns could be made ready for the task (worldwide, the number of such guns is perhaps a few hundred), they would need to be fired every minute or so forever. The manufacture of shells would be a problem. Shrapnel falling from the skies would be a problem. Noise would be a problem. However, since the guns would be mounted on ships, they could be kept at a distance from populated areas and moved around to generate a more uniform dust layer. As long as the guns were not pointed straight up, any dusts would fall harmlessly into the sea.

The technical and infrastructure problems with this ludicrous scheme are so profound it is hard to believe that anyone would seriously embrace it.

#### *Sunshades, Balloons, and Boogie Boards*

If an increase in planetary albedo will fix the climate, there are a variety of ways to manage it. After all, the albedo is related to reflectivity. Everyday experience tells us that white objects reflect more light than black objects do. A mirror reflects almost all the light that falls on it. A number of schemes based on this simple principle may be devised to cure a change in climate. One idea proposes placing huge solar shades in space. These space "parasols" would reduce the amount of sunlight impinging on the Earth. Only a small reduction would be needed (somewhat less than the increase in albedo required to produce the needed temperature compensation).<sup>8</sup> Hence the area on the ground that would have to be shaded is roughly 3 million square kilometers. Unfortunately, to create this equivalent shading effect on the Earth from space would require a sunshade about 100 times

other hand, can be generated photochemically. Since they are nucleated from the vapor phase, their sizes are initially much smaller than a micrometer. The larger size of the dust grains has two disadvantages. First, the grains fall more rapidly to lower altitudes, where they are readily removed from the atmosphere. Second, the larger-size particles are less efficient, for a fixed amount of mass, at increasing the albedo (Sections 3.2.2 and 6.5.2). Hence to produce the same increase in albedo, considerably more dust mass, compared with sulfate mass, would need to be injected.

8. The average albedo of the Earth is close to 0.33. To produce a 3-percent decrease in solar insolation, the albedo must increase by 0.03, which is close to 10 percent of the present albedo (Equation 14.1).

larger. Such a large size is needed because it must be placed at a great distance from the Earth, in a gravitationally stable position referred to as a *Lagrangian* point. In this position, the shade would cast only a partial shadow on the Earth, and an effect similar to a partial eclipse of the sun. Under these circumstances, the shade must be considerably increased in size to produce the same effective reduction in solar insolation as a shade near the Earth would produce.

Several researchers are exploring the idea of using balloons to increase the albedo. Balloons with shiny metallic coatings reflect sunlight very effectively. Imagine constructing a fleet of such balloons, filling them with helium, and letting them loose in the atmosphere. As they drifted around the world, the balloons would act like little clouds, reflecting sunlight away from the Earth. The balloons would be much smaller than a typical cloud, which can be hundreds of meters to several kilometers in size. We imagine the balloons to be only about 1 to a few meters in diameter. The balloons could be made to float in the lower stratosphere. Scientists already fly balloons there. So far it sounds easy enough.

How many reflecting balloons would you need to compensate for greenhouse warming? The answer is disconcerting. The cross-sectional area of the Earth is close to 120 million square kilometers. Accordingly, the effective area of shading required is crudely 4 million km<sup>2</sup> (or roughly 3 percent of the cross section).<sup>9</sup> Assume that the cross-sectional area of a typical balloon is about 4 square meters, or 7 feet in diameter (note that a spherical balloon does not reflect into space all the sunlight hitting it, depending on the time of day, varying amounts of the reflected light are reflected toward the surface). It follows that at least 1 trillion balloons will be required. A *trillion*

9. The area that must be covered by balloons is actually much larger than the average effective cross-sectional area of the Earth that must be shaded,  $4 \times 10^6$  km<sup>2</sup>. The area beneath the balloons is increased by a factor of two, because the *surface* area of the sunlit hemisphere is twice the cross-sectional area of the planet, and by another factor of two because the dark hemisphere, which rotates into daylight every 12 hours, must also contain balloons. Try an experiment. Take any spherical object—a globe, a basketball, or a grapefruit—and cut out a piece of cloth or aluminum foil equal in size to the cross-sectional area of the object. Now divide the material into pieces, and stick these randomly on the surface of the object. What fraction of the total surface appears to be covered by the material when you look at the object from different directions? Note that on average, the half of the sphere you can see at any time is about 25 percent covered. Working backward, to have an average shadow of 4 million km<sup>2</sup> projected onto the daylit hemisphere, an area four times as large, 16 million km<sup>2</sup>, must have balloons floating overhead at any instant.