CHAPTER 13

Global Climate Change and Air Pollution

Interactions and Their Effects on Human Health

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As the twenty-first century begins, the concern about many local and regional air pollutants has become less acute in the United States, Canada, and other developed nations. The implementation of regulatory measures and the development of cleaner technologies have resulted in the improvement of some indicators of air quality. Many developing countries have a different experience because they have not yet developed or adopted many of the regulatory measures of the industrialized world to reduce the levels of local and regional air pollution (United Nations Environment Programme 1991; World Bank 1997). However, for both developed and developing nations, evidence is growing that global climate changes caused by the emission of greenhouse gases may exacerbate the impacts of air pollution on human health and the environment (see Chapters 7 and 8). The focus of this chapter is on the interactions between greenhouse gas emissions and conventional air pollutants and their effects on human health.

Ever since the hazards of breathing soot and fumes were recognized midway into the industrial revolution, engineers have striven to develop cleaner technologies. Theoretically, the ideal engine, defined in terms of the cleanest by-products, would emit only carbon dioxide (CO_2) and water, neither being directly toxic to humans or the environment. Only recently has CO_2 been recognized as an undesirable by-product through its function as a greenhouse gas. The atmospheric concentrations of CO_2 and other greenhouse gases have been rapidly increasing (see Fig. 7.11) beyond any conditions observed in the historical record and represent a new environmental challenge (Houghton et al. 1996).

This chapter contrasts the ramifications of increases in greenhouse gas emissions against the backdrop of improving trends in conventional air pollution in the United States and Canada. A historical perspective reveals a new dimension of air pollution issues that are more regional and global in scale. This chapter then focuses on pollutants that are dependent on climatic conditions; climate change may actually make it more difficult to control the formation of some pollutants, such as ozone. Finally, the broad scope of potential health effects of climate change worldwide is briefly reviewed.

A Historical Perspective on Air Pollution

From Local to Regional to Global

Historically, the developed nations have gone through a series of transitions with respect to air pollution problems. By the mid-1800s, the combustion of fossil fuels had fouled the urban environment in industrial cities. At that time, smoke, soot (particles), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) were the predominant emissions of concern. These pollutants caused respiratory irritation, hindered visibility, and blackened buildings. Later, the advent of the automobile introduced the problem of increasing concentrations of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the urban environment. As chemical precursors to ground-level ozone, these pollutants resulted in a new type of "photochemical smog," consisting primarily of ozone whose formation was catalyzed by sunlight.

After the 1952 disaster in London, England, where a four-day period of smog caused an estimated 4,000 deaths (Logan 1953), it became strikingly clear that local accumulations of air pollution were hazardous. The adage, "the solution to pollution is dilution," was fervently followed, leading to the construction of higher smokestacks and the relocation of polluting industries farther away from urban centers. While local air quality benefited from the greater dispersion of pollution afforded by higher smokestacks, problems of regional air pollution, such as "acid rain," emerged or were exacerbated.

Acid rain demonstrates the shortcomings of addressing pollution from only a local perspective. The regional problem of acid rain was actually first described in the mid-1800s in reference to the effect of industrial emissions on precipitation in the British midlands. It has long been recognized that acid rain is widespread in northern Europe and eastern North America. By the mid-1980s, roughly half of the sulfuric acid rain falling in eastern Canada originated in the United States, just as much of the Scandinavian acid precipitation has been traced to industrialized areas of central Europe and the United Kingdom (Schindler 1988). Recent studies have led to discoveries of areas affected by acid rain in the western United States, Japan, China, the former Soviet Union, and South America.

Transboundary Air Pollution

Toxic air pollutants such as persistent organic pollutants (POPs) can travel long distances. POPs include pesticides, such as aldrin, chlordane, DDT, dieldrin, heptachlor, and toxaphene; industrial chemicals like polychlorinated biphenyls (PCBs); and industrial or incineration by-products such as dioxin and furans. POPs are highly fat soluble; they degrade very slowly in the environment and can bioaccumulate to high levels as they move up the food chain. For example, dioxin bioaccumulates through terrestrial food webs and can become concentrated in milk and other dairy products. Indigenous people near the Arctic, who rely on fatty foods high on the food chain, such as polar bear, seal, and fish, can receive considerable exposure to POPs, and the placentas of pregnant women in these areas are often found to have high levels of POPs that pose fetal risk. Some POPs can act as endocrine disrupters, mimicking the body's hormones. Estrogenic chemicals (including some organochlorines such as DDT, some PCBs, dioxin, and furans) may be responsible for declining sperm counts and the rising incidence of abnormalities in the human male reproductive tract (Jensen et al. 1995).

The transport of POPs can transcend international boundaries, as detailed in a report of the Commission for Environmental Cooperation (CEC), which was established under the North American Free Trade Agreement (*CEC 2000*). For example, 15–25 percent of the dioxin deposited in Lake Michigan comes from sources as far away as southern Texas. Up to 90 percent of POPs applied as agricultural pesticides are retained in the atmosphere or are revolatilized. Atmospheric deposition currently contributes the majority of the total yearly input of PCBs to Lake Superior (Environmental Protection Agency [EPA] 1996a). POPs eventually concentrate in water, soil, and wildlife in the cooler, northern latitudes because of normal atmospheric convection patterns and the tendency of POPs to revolatilize many times, termed the *grasshopper effect.* When the chemical is cooled, it condenses and precipitates out of the atmosphere, so that deposition tends to prevail over evaporation at high latitudes. POPs also degrade more slowly at cold temperatures.

Polluted air masses from industrial sources have also been tracked across the Atlantic Ocean and the Arctic by documenting unique trace metal content within these air masses (Schindler 1988). In 1998, some air pollution in the northwestern United States was even found to have originated in Asia, a transport process that would generally take 4–10 days (Monastersky 1998). Dust clouds from Asia, tracked by satellite in the spring of 1998, deposited detectable levels of arsenic, copper, lead, and zinc at the pristine site of Crater Lake, Oregon.

Global warming is the ultimate example of the global effect of air pollution, on a par with the global threat of stratospheric ozone depletion

(Chapter 7). The geographic point of emission of greenhouse gases has little relation to the effects of this phenomenon. Aggregated local and regional emissions are having a global impact whose full implications for the world's climate are still being learned.

Trends in Air Pollutants and Greenhouse Gases

In 1972, under provisions of the U.S. Clean Air Act, the newly established EPA was required to set national ambient air quality standards (NAAQSs) for current "criteria" pollutants deemed to be potentially hazardous to human health. The term *criteria* is an administrative designation by the EPA for carbon monoxide (CO), NO_2, particulate matter (PM), SO_2, ozone, and lead (Pb). The standards covering these pollutants were designed to be protective of the most vulnerable subgroups within the population, such as asthmatics or persons with emphysema. In 1997, EPA revised the original health-based standards for criteria air pollutants to add new standards for particles that were less than 2.5 microns in diameter ($PM_{2.5}$).

Since 1970, the emissions and concentrations of air pollutants in the United States have decreased substantially despite large increases in total population, vehicle miles traveled (VMT), and gross domestic product (GDP). From 1970 to 1996, the U.S. population increased by 29 percent, VMT increased by 121 percent, and the GDP increased by 104 percent, yet aggregate emissions of *criteria air pollutants* decreased by 32 percent (Fig. 13.1). Changes in the emissions of individual pollutants range from a 98 percent decrease for lead to an 11 percent increase for NO_2. Table 13.1 summarizes the percentage changes in national air quality concentrations and emissions. The experience in Canada has been similar (*Environment Canada 2000*). Nevertheless, direct exposure to air pollution continues to affect human health adversely in the United States and Canada. For example, a recent study of 11 Canadian cities showed an increase of 8 percent in daily rates of nontraumatic mortality associated with days of high levels of air pollution for NO_2, ozone, SO_2, and CO (Burnett et al. 1998).

While emissions of most criteria air pollutants have been decreasing, emissions of CO_2 from fossil fuel combustion in the United States grew by 9 percent between 1990 and 1996 (*EPA 2000a*). Figure 13.1 compares trends in the emission of criteria air pollutants (along with population, VMT, and GDP) with trends in the emission of CO_2. Thus, as cleaner technologies mandated under the U.S. Clean Air Act have reduced the levels of criteria pollutants (except for NO_2 and ozone in some regions), the emissions of greenhouse gases have been relatively unaffected by regulations. In essence, while the United States may be benefiting from cleaner air nationally, the country continues to emit substantial amounts of CO_2, exacerbating the problem of global climate change.

The catalytic converter developed for motor vehicles illustrates this

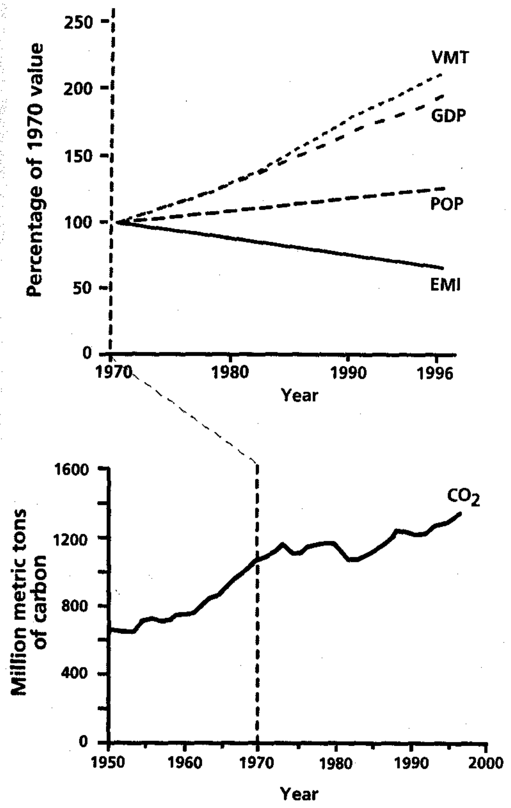

Figure 13.1 U.S. trends in emissions of criteria air pollutants, emissions of carbon dioxide, and related factors. Emissions of volatile organic compounds (VOCs) are included in the emissions of criteria air pollutants, since tropospheric ozone is created from VOCs rather than emitted directly from a source of ozone. *VMT,* vehicle miles traveled; *GDP,* gross domestic product; *POP,* population; *EMI,* emissions of criteria air pollutants. *Source:* Redrawn from *Environmental Protection Agency 1999a,* Executive Summary, p. 3, and *Marland et al. 1999.*

paradox of trading one air pollution problem for another. Vehicles now sold in the United States emit 96 percent less CO, 98 percent fewer hydrocarbons, and 90 percent less NO_x than vehicles sold in the early 1970s (*EPA 1999a*). Some of these reductions are the result of catalytic converter technology. As exhaust gases pass over the catalysts, chemical reactions convert pollutants (hydrocarbons, NO_x, CO) into harmless gases (CO_2, nitrogen) and water: (1) hydrocarbons combine with oxygen forming CO_2, (2) NO_x react with CO to produce nitrogen and CO_2, and (3) NO_x react with hydrogen to produce nitrogen and water vapor.

While greatly reducing emissions of CO, NO_x, and hydrocarbons, catalytic converters generate nitrous oxide (N_2O), a greenhouse gas that is presently unregulated and has 310 times the *global warming potential* of CO_2 (see Chapter 7). Combined emissions of greenhouse gases from stationary and mobile sources have increased by 21 percent from 1990 to 1996, primarily because of rising rates of N_2O generation in motor vehicles (*EPA 2000a*). Cars with catalytic converters emit up to five times the N_2O of cars without the devices, although the most current generation of converters have somewhat improved.

Table 13.1 Long-Term Change in U.S. National Air Quality Concentration and Emissions

Criteria Air Pollutant	Air Quality Concentration Percentage Change 1978–97	Emissions Percentage Change 1970–97
Carbon monoxide	−60	−32
Lead	−97	−98
Nitrogen dioxide	−25	+11
Ozone	−30 (1 hr)	−37
Particulate matter (<10 microns)	Not available	−75
Sulfur dioxide	−55	−35

Source: Adapted from *Environmental Protection Agency 1999b*, 9.

Fossil Fuels: The Common Source of Air Pollutants and Greenhouse Gases

Fossil fuel combustion is a common source of emissions of CO_2 and the six criteria air pollutants: CO, NO_2, PM, SO_2, ozone, and lead (Table 13.2; EPA 1997). (See also Box 13.1.) The use of fossil fuels, particularly gasoline, also releases air toxics, such as benzene, toluene, and VOCs (EPA 1997). The term *air toxic* is an administrative designation by the EPA for a variety of air pollutants, largely volatile compounds and heavy metals, that are not designated as criteria air pollutants.

Fossil fuel combustion produces nearly all of the CO_2 released into the atmosphere from human activities. As the most abundant greenhouse gas, CO_2 accounts for 81 percent of the total U.S. emissions of greenhouse gases, equaling 1,788 million metric tons of carbon equivalent (MMTCE) in 1996. This unit of measure is used because greenhouse gases differ in their global warming potential (Chapter 7). Although greenhouse gases such as methane (CH_4), N_2O, and chlorofluorocarbons (CFCs) have a greater warming potential than does CO_2, the magnitude of its emissions ensures that CO_2 contributes the most to enhanced greenhouse warming, and CO_2 levels are the focus of many projections of climate change. CO_2, CH_4, and N_2O occur naturally in the atmosphere, but human activities have substantially increased their concentrations. Since the mid-1800s, these greenhouse gases have increased by 30, 145, and 15 percent, respectively (Houghton et al. 1996). While the burning of fossil fuel is the largest source of CO_2, agriculture and decomposition of landfills are important sources of CH_4 and N_2O (*EPA 2000a*). Table 13.2 shows trends for all greenhouse gas emissions and sinks, presented in MMTCE units. Note the prominence of fossil fuel combustion.

BOX 13.1

Legacy of Gasoline Additives: Lead and Methyl Tertiary Butyl Ether

Lead interferes with brain development and has been associated with lower intelligence quotients (IQs) in children. Even relatively low blood lead levels (i.e., 10–25 micrograms per deciliter) have been shown to affect IQ in children. Elevated levels of lead in the blood of adults have been associated with high blood pressure. The use of tetraethyl lead as a gasoline additive in the United States resulted in widespread airborne dissemination of lead oxide, particularly in urban areas. After the phaseout of leaded gasoline in the United States, emissions of lead from transportation sources rapidly declined, and between 1977 and 1996, ambient concentrations of lead fell by 97 percent. This source of emissions has been almost eliminated in the United States. Blood lead levels in children have paralleled this reduced exposure. However, other sources of lead in the environment retain the potential to affect children. The legacy of lead from gasoline remains in elevated lead content in urban dusts and soils. Even though lead-based paint has been banned in the United States since 1978, children can be exposed if they reside in older housing stock or in older homes that have been renovated. In addition, lead is still used extensively as an additive to gasoline in other parts of the world, resulting in widespread exposure of humans to lead.

Lead is not the only additive to gasoline that has become widely distributed in the environment. The additive methyl tertiary butyl ether (MTBE) has recently been recognized as a significant contaminant of groundwater supplies in the United States, raising concerns about the quality of drinking water (*EPA 2000b*). MTBE is potentially carcinogenic to humans and gives drinking water an unpleasant taste and odor. Ironically, the purpose of adding MTBE to gasoline was to reduce atmospheric pollution in order to comply with the 1990 amendments to the U.S. Clean Air Act.

Mercury is an example of an air toxic whose emissions stem from burning fossil fuels, especially in coal-fired power plants. Other sources include waste incinerators, landfills, copper and lead smelting operations, and cement manufacturing plants. Anthropogenic emissions have increased the global atmospheric burden of mercury by two- to fivefold (*CEC 2000*). A major proportion of the mercury present in the atmosphere is elemental mercury, which is extremely volatile and, in its gaseous form, has an estimated atmospheric residence time ranging from 3 months to 2 years. Organic methyl mercury can bioaccumulate through the food chain in aquatic systems to reach toxic levels in predatory fish, as was the case in Minimata Bay, Japan, where severe birth defects (e.g., cerebral palsy) resulted from fetotoxicity in pregnant women who consumed contaminated fish (Koos and Longo 1976). While the mercury in Minamata was not airborne in origin, it alerted the world to the dangers of mercury in the environment. Currently, 5 Canadian provinces and over 35 U.S. states have issued health advisories to reduce the consumption of certain freshwater fish that are known to contain excessive levels of mercury.

Table 13.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMTCE), 1990–1996

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CO_2 (Totals)	1,348.3	1,333.2	1,353.4	1,385.6	1,408.5	1,419.2	1,471.1
Fossil fuel combustion	1,331.4	1,316.4	1,336.6	1,367.5	1,389.6	1,398.7	1,450.3
Natural gas flaring	2.0	2.2	2.2	3.0	3.0	3.7	3.5
Cement manufacture	8.9	8.7	8.8	9.3	9.6	9.9	10.1
Lime manufacture	3.3	3.2	3.3	3.4	3.5	3.7	3.8
Limestone and dolomite use	1.4	1.3	1.2	1.1	1.5	1.8	1.8
Soda ash manufacture and consumption	1.1	1.1	1.1	1.1	1.1	1.2	1.2
Carbon dioxide manufacture	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Land use change and forestry (sink)[a]	(311.5)	(311.5)	(311.5)	(208.6)	(208.6)	(208.6)	(208.6)
CH_4 Totals	169.9	171.1	172.5	171.9	175.9	179.2	178.6
Stationary sources	2.3	2.3	2.4	2.3	2.3	2.4	2.5
Mobile sources	1.5	1.4	1.4	1.4	1.4	1.4	1.4
Coal mining	24.0	22.8	22.0	19.2	19.4	20.3	18.9
Natural gas systems	32.9	33.3	33.9	34.1	33.9	33.8	34.1
Petroleum systems	1.6	1.6	1.6	1.6	1.6	1.6	1.5
Petrochemical production	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Silicon carbide production	+	+	+	+	+	+	+
Enteric fermentation	32.7	32.8	33.2	33.6	34.5	34.9	34.5
Manure management	14.9	15.4	16.0	16.1	16.7	16.9	16.6
Rice cultivation	2.5	2.5	2.8	2.5	3.0	2.8	2.5
Agricultural residue burning	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Landfills	56.2	57.6	57.8	59.7	61.6	63.6	65.1
Wastewater treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9

Many “cobenefits” can be achieved by reducing the emissions of the fossil fuels that are a common source of criteria air pollutants, air toxics, and greenhouse gases. For example, if nations abided by the Kyoto Protocol to reduce their emissions of greenhouse gases (see Chapter 6), what might be the benefits in terms of the effects on human mortality? An interdisciplinary working group examined this question by combining models of energy consumption, carbon emissions, and associated emissions of PM. PM has been linked to increased mortality (Dockery and Pope 1994; Pope et al. 1995; Samet et al. 2000). Even at levels below the NAAQSs, PM increases daily rates of cardiorespiratory mortality and total mortality in

Gas/Source	1990	1991	1992	1993	1994	1995	1996
N_2O (Totals)	92.3	94.4	96.8	97.1	104.9	101.9	103.7
Stationary sources	3.7	3.7	3.7	3.8	3.8	3.8	4.0
Mobile sources	13.2	13.9	14.8	15.6	16.3	16.6	16.5
Adipic acid	4.7	4.9	4.6	4.9	5.2	5.2	5.4
Nitric acid	3.4	3.3	3.4	3.5	3.7	3.7	3.8
Manure management	2.6	2.8	2.8	2.9	2.9	2.9	3.0
Agricultural soil management	62.4	63.4	65.2	64.1	70.4	67.2	68.6
Agricultural residue burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Human sewage	2.1	2.1	2.2	2.2	2.3	2.2	2.3
Waste combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs, and SF_6 (Totals)	22.2	21.6	23.0	23.4	25.9	30.8	34.7
Substitution of ozone-depleting substances	0.3	0.2	0.4	1.4	4.0	9.5	11.9
Aluminum production	4.9	4.7	4.1	3.5	2.8	2.7	2.9
HCFC-22 production	9.5	8.4	9.5	8.7	8.6	7.4	8.5
Semiconductor manufacture	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Electrical transmission and distribution	5.6	5.9	6.2	6.4	6.7	7.0	7.0
Magnesium production and processing	1.7	2.0	2.2	2.5	2.5	3.0	3.0
Total Emissions	1,632.7	1,620.2	1,678.0	1,678.0	1,715.3	1,731.1	1,788.0
Net Emissions (Sources and Sinks)	1,321.2	1,308.7	1,334.2	1,469.4	1,506.7	1,522.5	1,579.5

Source: Environmental Protection Agency 2000a, ES-3.

Note: Totals may not sum due to independent rounding. +, does not exceed 0.05 MMTCE.

[a] Sinks are included only in net emissions total. Estimates of net carbon sequestration due to land use change and forestry activities exclude nonforest soils and are based partially upon projections of forest carbon stocks.

the United States and Europe (Katsouyanni et al. 1993). In children, PM levels also correlate with increased hospital admissions, school absences, and medication use, as well as a reduction in lung function (measured as peak respiratory flow rates) (Bascom et al. 1996). Under a climate policy scenario approximating that of the Kyoto Protocol (e.g., the United States emitting 7 percent below 1990 levels of greenhouse gas emissions), approximately 700,000 premature deaths due to exposure to PM might be averted annually by the year 2020 as compared with the business-as-usual forecast (Working Group on Public Health and Fossil-Fuel Combustion 1997). This analysis showed the potential near-term cobenefits of long-term policies to mitigate global climate change.

Climate Change and Levels of Air Pollutants

Secondary Air Pollutants

Fluctuations in weather have the most influence on pollutants that arise from chemical reactions in the atmosphere. These "secondary pollutants," such as ozone and acid rain, are derived from a mixture of pollutants directly emitted, which are termed *primary pollutants.* Even with the improving air quality in the United States and Canada, urban ozone pollution and regional acid rain persist as problems and have the potential to be exacerbated if air temperatures warm. Ozone, as described in Chapter 7, forms secondarily in the lower atmosphere by a temperature- and sunlight-dependent reaction between NO_x and VOCs, precursors of the formation of ozone. The major source of NO_x in North America is fossil fuel combustion used in transportation and electric utilities. Since 1970, the number of vehicle miles traveled in the United States has increased at a faster rate than that of the overall population (see Fig. 13.1). From 1970 to 1994, car ownership in Canada rose from 310 to 484 vehicles per 1,000 people (Last et al. 1998). Transportation is also a major source of anthropogenic VOCs. Other sources of VOCs include incinerators, gasoline vapors, paints and solvents, and some trees or other vegetative sources.

The Influence of Weather on Ozone Formation

Tropospheric ozone, as a photochemical oxidant and the main ingredient of urban smog, is pervasive and difficult to control. The reaction between NO_x and VOCs to form ozone is catalyzed by ultraviolet radiation and requires relatively high ambient air temperatures (see Chapter 7). Meteorological factors that could theoretically influence the levels of tropospheric ozone include ultraviolet radiation, air temperature, wind speed, and atmospheric mixing and transport.

In general, there is a direct correlation between temperature and levels of ozone (Kamens et al. 1982; Grey et al. 1987; Samson 1988). Increases in atmospheric temperature accelerate photochemical reaction rates in the atmosphere and tend to increase the rates at which tropospheric ozone and other oxidants (e.g., hydroxyl radicals) are produced (Hatakeyama et al. 1991; Morris et al. 1995). Studies of ambient temperature have reported that successive episodes of high temperatures characterize years with seasonally high levels of ozone. The relationship is nonlinear, and above a temperature of 32°C (90°F), there is a strong correlation between temperature and levels of ozone (Fig. 13.2). However, levels of ozone may not always increase with an increase in temperature. For example, the production of ozone is reduced when the ratio of VOCs to NO_x is low (see Fig. 7.8).

In the eastern United States and in Europe, the majority of days when the levels of ozone exceed air quality standards occur in conjunction with

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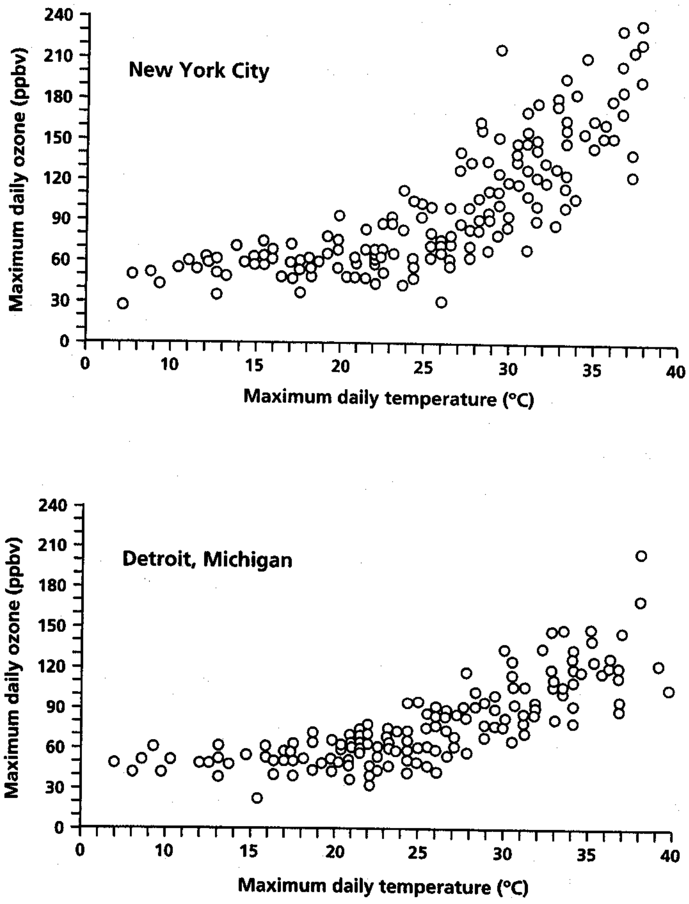

Figure 13.2 Relationship between maximum daily ozone concentration and maximum daily temperature in New York City and Detroit, Michigan. *Source:* Redrawn from Environmental Protection Agency 1996b, Figure 3.9.

slow-moving high-pressure systems around the time of the summer solstice (National Research Council [NRC] 1991). This is the period of greatest sunlight, when solar radiation is most intense and air temperatures are high. The relatively high levels of ozone in the United States during 1988 and 1995 were probably due in part to hot, dry, and stagnant conditions (Patz et al. 2000). During 1995, one of the hottest years on record, 32 percent of Americans, or 71 million people, resided in counties in which ozone levels exceeded the NAAQSs (EPA 1996a). Episodes of high levels of ozone last three to four days on average and extend over a large area (i.e., greater than 600,000 square kilometers).

Several factors associated with high-pressure systems are conducive to the photochemical production of ozone. Large high-pressure systems often create an inversion of the normal temperature profile, trapping pollutants in the shallow boundary layer at the earth's surface. Winds associated with major high-pressure systems are generally light, allowing greater accumulation of pollutants. Clear, warm conditions generally associated with large high-pressure systems afford ample sunlight to catalyze the photochemical production of ozone (NRC 1991).

Conditions in Los Angeles illustrate how the combined characteristics of meteorology and topography can adversely affect the air. This area is dominated by a persistent high-pressure system off the Pacific Ocean, which forms an inversion layer trapping pollutants over the city. Topography (river valleys or regions surrounded by mountains) also provide pockets to trap accumulations of primary pollutants and ozone, often capped by an inversion layer. Because of the region's low latitude and relatively clear skies, plenty of ultraviolet radiation is available for photochemical production of tropospheric ozone. A similar situation occurs in Mexico City (Box 13.2).

Trends in summer climatic conditions in the United States may have become more suitable for the formation of ground-level ozone. From 1949 to 1995, the number of summer heat waves (defined as more than three consecutive days with average apparent temperatures exceeding the 85th percentile) has increased by 20 percent, according to one study (Gaffen and Ross 1998). Climatic conditions could become more suitable for ozone formation under projections of global warming, but the extent of ozone formation will also depend on air mass and wind conditions.

The Influence of Weather on Ozone Transport

Urban smog has long been viewed as a local issue. However, both ozone and its precursors can travel relatively long distances in the atmosphere and be transported from region to region and across international boundaries. Such processes of transboundary pollution transport have implications for distant downwind populations. Analyses by such groups as the Ozone Transport Assessment Group (OTAG) have confirmed that, in the eastern United States, some areas experience a considerable influx of ozone across air boundaries and cannot meet air pollution standards by local measures alone (*Guinnup and Collom 1997*).

The distance that ozone can be transported ranges from 150 to 500 miles (roughly 240 to 800 kilometers). For example, ozone precursors from New York City are transported by prevailing winds on a roughly 200-mile northeast trajectory through Connecticut and as far as northeastern Massachusetts (Cleveland et al. 1976). Consequently, southwestern Connecticut has the highest concentrations of ozone in this region. The mid-Atlantic and northeastern United States are affected by even broader regional ozone transport. While the highest emissions of the ozone precursors,

BOX 13.2

Climate, Topography, and Fossil Fuel Emissions: The Special Case of Mexico City

Mexico City illustrates how geographic features can exacerbate local and regional air pollution. Mexico City is located in a basin that lies at a high altitude (2,240 meters above sea level) and is surrounded on the east, south, and west by mountain ranges that impede the movement of air over the basin. Frequent thermal inversions in the winter increase the accumulation of pollutants. Prevailing winds from the northeast tend to blow pollutants emitted from industrial sites and automobiles toward residential areas in the southwest.

One local health study examined biopsies of nasal mucosa from healthy residents of southwest Mexico City and compared the results to biopsies from residents of Veracruz, a nonpolluted Mexican port city. Of those subjects who had lived in southwest Mexico City for more than 60 days, 78 percent had evidence of precancerous squamous cell dysplasia, compared to 0 percent of those from Veracruz and 11 percent of those who had resided in southwest Mexico City for less than 30 days .

While more than 30,000 industries are located within the basin, emissions from automobiles are the greatest source of air contamination in Mexico City. The city's rapidly growing fleet numbered over four million automobiles in 1994, with growth rates in the late 1980s and early 1990s averaging about 5 percent annually. In the central city, where traffic congestion is greatest, the emissions of volatile organic compounds and nitrogen oxides, which are the precursors to the formation of ozone, are extremely high. The city's high altitude also leads to a relatively high influx of ultraviolet radiation, which promotes the formation of secondary air pollutants such as ozone. In 1992, the city's southwest area experienced more than 1,000 hours when the ambient concentrations of ozone exceeded the Mexican norm of 110 parts per billion for a maximum period of one hour.

Regionally, elevated levels of ozone, in combination with acid rain, have been blamed for extensive damage to the ecosystem in the surrounding mountain forests. Phytopathologists have documented reduced chlorophyll content and stunted growth in the pine forests, which may be attributable to ozone damage. Since the integrity of these mountainside forests is essential for the collection and filtering of water that eventually ends up as the city's drinking water, such disruption to the ecosystem has effects on economics and human health beyond the direct effects of the pollutants in the city.

VOCs and NO_x, come from large urban metropolitan areas, the largest elevated point source of NO_x emissions comes from the industrial Ohio River valley (*Guinnup and Collom 1997*). Based on spatial patterns and transport considerations, general control measures should clearly target urban nonattainment areas (areas that do not meet NAAQSs), as they contribute significantly to their own ozone problems. However, with the Ohio River valley's high density of NO_x point sources, NO_x controls targeted for this region may be an important measure for effectively reducing ozone pollution for the entire eastern United States.

The Health Effects of Ozone

Ozone causes symptoms of respiratory and mucous membrane (eyes, nose, and throat) irritation. As a strong oxidant, ozone can cause both cellular and structural damage in the lung. Three types of respiratory responses to ozone exposure are (1) irritative cough; (2) reduced lung capacity, as well as decreased expiratory flow rates; and (3) inflammation of the airway lining or submucosa (Bascom et al. 1996). An inflammatory response usually develops within an hour after exposure and persists for up to 24 hours. Exercise, of course, can increase the dose inhaled because of higher ventilation rates, and the most vulnerable populations include asthmatic children in the northeastern United States, where daily ozone levels may remain elevated for six to eight hours (Bascom et al. 1996).

Epidemiological studies of emergency room and hospital admissions indicate ozone's significant health effect. During the summertime (when many viral respiratory infections have subsided), exposure to ozone contributes an estimated 10–20 percent of all admissions to hospital due to respiratory conditions. On the days with the highest levels of ozone, exposure to ozone can account for nearly half of all respiratory admissions (EPA 1996a). Even levels below the NAAQSs can cause reversible decrements in respiratory function, including airway constriction, reduced lung volume, irritating cough, and chest pain (Bascom et al. 1996).

The effects of chronic exposure to ozone are less well understood. However, an analysis of pulmonary function data from the second National Health and Nutrition Examination Survey (NHANES II) revealed some association between ambient concentrations of ozone and the loss of lung function over time (Schwartz 1989). Some evidence also suggests that increased incidence and severity of asthma are related to exposure to ozone, although it is difficult to separate the effect of exposure to ozone from concomitant exposure to PM (EPA 1996a). In Mexico City, ozone has been linked to increased admissions to hospital for lower respiratory infections and asthma in children (Romieu et al. 1996). Ozone has been implicated in the exacerbation of asthmatic reactions by reducing the amount of allergen required to induce symptoms (Koren and Bromberg 1995; Koren and Utell 1997).

Acid Rain

SO_2 and NO_x oxidize via reactions with hydroxyl radicals and hydrogen peroxide in the atmosphere to form sulfuric acid and nitric acid, respectively (see Chapter 7). Acid deposition can be either wet or dry. Wet deposition occurs when emissions of sulfur oxides, primarily SO_2, and nitrogen oxides are transformed into acids in the atmosphere and then fall to earth as fog, rain, hail, or snow. Dry deposition occurs when these acid aerosols are brought to earth by gravity or other nonprecipitative means.

The National Surface Water Survey, which was conducted by the EPA, examined acid-sensitive areas of the United States comprising 1,180 lakes and 4,670 streams. Atmospheric deposition was found to be the dominant source of acid anions in 75 percent of the acidic lakes and in 47 percent of the acidic streams (Baker et al. 1991). According to the National Acid Precipitation Assessment Program (NAPAP), sulfur compounds from fossil fuel emissions are major precursors in the acidification of these surface water bodies (NAPAP 1991).

In the United States and Canada, coal-fired power plants, oil and gas processing, and the smelting of sulfur-rich ores account for about two-thirds of SO_2 emissions (*CEC 2000*). While global sulfur emissions from fossil fuel combustion are comparable to those from natural sources, over 90 percent of atmospheric sulfur in northern Europe and eastern North America is anthropogenic in origin. These findings have displaced earlier claims that volcanoes, trees, salt marshes, or other natural sources were primarily responsible for acidification in these regions (Schindler 1988).

Although the causes of many regional patterns of acid deposition remain uncertain, several of the factors that affect ozone formation also influence acid deposition (Penner et al. 1989). Higher temperatures accelerate the oxidation rates of SO_2 and NO_x to sulfuric and nitric acids, further potentiating acid formation. For example, high temperatures accelerate the production and concentration of hydrogen peroxide. This, in turn, increases the oxidation rate of SO_2 to sulfuric acid and ultimately the production of acid rain.

The Health Effects of Sulfur Dioxide

SO_2 is an irritant that can inflame the lining of the respiratory tract and may have been a key component in the smog disaster that killed thousands in London in 1952. In Ontario, Canada, sulfate levels have been found to correlate significantly with relative humidity in the summer (Bates and Sizto 1987), and the concentration of SO_2 was a predictor of hospital admissions for respiratory causes in the summer. On days with peak levels of pollution, summertime haze (comprising mostly ozone and acid aerosols) was associated with roughly half of all respiratory admissions (Thurston et al. 1994). These atmospheric chemical reactions are, therefore, essential in understanding the potential risk to health of changing climate conditions, including temperature and humidity.

Potential Effects of Climate Change on Air Pollution in the United States

As population growth and increases in energy consumption lead to increased fossil fuel emissions, the accumulation of CO_2, once thought to be a "clean" and harmless by-product of combustion, now poses indirect public health and ecological ramifications via global climate change (see "Possible Pathways of the Effect of Global Climate Change on Public Health," below). The change that is likely to have the most effect on conventional air pollutants is an increase in temperature.

Warmer temperatures due to climate change, all other things held constant, may increase concentrations of ozone and acid aerosols, as well as emissions of particulates and allergens (see under "Climate Variability, Biomass, Air Quality, and Health: Forest Fires and Allergens," below). A rise in temperature could affect concentrations of ozone by modifying the factors that affect the production of ozone (NRC 1991):

1. Elevated temperature—Ozone formation in the atmosphere is highly dependent on temperature. Urban areas tend to absorb and hold more heat, a process termed the *urban heat island effect.* The urban heat island effect can drive up air temperatures by 4–5°C or more (Landsburg 1981). The urban heat island may significantly contribute to elevation of ozone levels by adding thermal energy that can enhance the chemical formation of ground-level ozone (Quattrochi et al. 2000). Also, NO_x and VOC precursors of ozone are concentrated in congested cities. Urban air quality could therefore be particularly altered by higher global temperatures.
2. Increased frequency and intensity of stagnation periods—Climate change could result in more frequent or intense high-pressure systems, which provide favorable conditions for the reactions that produce ozone in the atmosphere.
3. Increased water vapor concentration—In addition to enhancing the formation of acid aerosols, increases in water vapor can potentiate the formation of ozone (Penner et al. 1989).
4. Increased emissions of precursor pollutants—Forests, shrubs, grasslands, and other sources of natural hydrocarbons (VOCs) emit greater quantities of these compounds at higher temperatures. Soil microbial activity may also increase with warmer temperatures, leading to an increase in NO_x emissions.

On the other hand, factors that could lead to reduced ozone concentrations include the following:

1. Increased cloud cover—A more vigorous hydrological cycle due to global warming could lead to an increase in cloudy days. More cloud cover, especially in the morning hours, could diminish reaction rates, thus lowering ozone formation.
2. Increased thickness of the boundary layer of air—Higher temperatures might be associated with greater convection, resulting in reduced atmospheric stability and higher wind speeds. If precursor pollutants

(VOCs or NO_x) are mixed in a greater volume of air, they will be less concentrated and less ozone will be formed (Smith and Tirpak 1989). The net effect of these factors is unclear; however, modeling studies combining these variables are being performed to assess the effects of climate change on air quality.

Modeling Studies of Air Quality and Climate Change

The most direct effect of climate change on air quality is the influence of increased temperature on the formation of ozone. Although studies have found that concentrations of ozone increase as temperature rises, the estimated magnitude of the effect varies considerably. This variation stems in part from limitations in the ability of atmospheric models to simulate complex photochemical reactions in the atmosphere. The presence of feedback effects between a rise in temperature and the formation of ozone is also a complicating factor. Therefore, the predictions of the modeling studies must be carefully interpreted in light of these limitations. Some of the modeling studies and their results are described below.

Grey et al. (1987) examined the effects of increased temperature and decreased stratospheric ozone (and thus more ultraviolet radiation [Chapter 7]) on the formation of ground-level ozone in eight U.S. cities: Los Angeles, New York, Philadelphia, Washington, D.C., Phoenix, Tulsa, Nashville, and Seattle. According to the model, the concentration of ground-level ozone would rise by about 2–4 percent for a 2°C increase in temperature and by about 5–10 percent for a 5°C increase in temperature; a loss of 15–30 percent of stratospheric ozone would have a greater effect. The most polluted cities showed the strongest response, implying that the effects of warming would be worse in those places where the concentration of ground-level ozone is already relatively high. A follow-up study of a possible 4°C rise in temperature indicated that the size of the area out of compliance with national standards for ozone would double in the San Francisco Bay region and nearly triple in the midwestern and southeastern United States (Morris et al. 1989).

A broader study of ground-level ozone in Memphis, Dallas, Philadelphia, Baton Rouge, and Atlanta included the influence of temperature on biogenic emissions of hydrocarbon (Morris et al. 1992). The study estimated that the control of VOC emissions required to attain the ozone NAAQS would increase approximately in proportion to the local increases in temperature. If perturbations to the stratospheric ozone layer were combined with increases in temperature, the stringency of the required controls would increase even further. In a subsequent study, model simulations showed that the concentrations of ozone in the northeastern United States would increase if temperatures rose by 4°C without the added complication of stratospheric ozone depletion (Morris et al. 1995).

The analysis considered the amount of upward penetration of emission plumes, the mass of hydrocarbons emitted from biogenic sources, and the response of evaporative emissions of hydrocarbons in gasoline from motor vehicles.

These studies of the effects of climate change on air quality must be considered indicative but by no means definitive. Many aspects of weather affect air quality, and ultimately climate is largely a general aggregate of weather patterns. Important local weather factors may not be adequately represented in these models. These models do, however, include such important factors as temperature stratification (or thermal inversions) and clouds, which play an important role in mixing and redistributing air pollutants (Oke 1987). The models used to simulate changes in air quality as a result of increases in temperature and ultraviolet radiation do not address issues such as the frequency of episodes of stagnant weather, which is associated with the highest concentrations of ozone observed over broad areas. Regional-scale changes in simulations of climate are inconsistent from model to model, and thus predicted changes in weather patterns carry much uncertainty. However, the trend in all models of global climate change is to predict higher maximum and minimum temperatures (Houghton et al. 1996), and associated summer episodes of weather stagnation have been observed more frequently in the United States (Gaffen and Ross 1998).

Climate Variability, Biomass, Air Quality, and Health: Forest Fires and Allergens

Extremes in climate, such as heat waves or severe droughts, are difficult to predict but are anticipated to become more prevalent under climate change scenarios. Severe droughts with accompanying forest fires have the potential to affect air quality. For example, in 1997–98, El Niño–driven droughts (see Chapter 8) contributed to the development of expansive forest fires in Indonesia, Mexico, Central and South America, Florida, Canada, and several other parts of the world. The extended duration of biomass burning affected air quality over regions far greater than the areas where burning actually occurred. The exposure of humans to fire smoke has been associated with irritation of the throat, lungs, and eyes. In addition, fire smoke carries a large amount of fine particles, which exacerbate respiratory problems, such as asthma and chronic obstructive pulmonary disease (Duclos et al. 1990).

In June and July of 1998, 2,277 fires burned approximately 500,000 acres in both rural and urban areas in Florida (Karels 1998). An analysis of records from several hospitals in Volusia and Flagler Counties showed that visits to the emergency department increased for asthma (by 91%), bronchitis (132%), and chest pain (37%) (Centers for Disease Control and Prevention 1999).

During the spring of 1998, low rainfall in Guatemala, Nicaragua, Honduras, El Salvador, Costa Rica, and several parts of Mexico caused tropical forested areas, usually too humid to burn on their own, to become vulnerable to fire (Agency for International Development 1998). By May 1998, thousands of fires had burned more than one million acres in Central America and emitted large quantities of smoke into the atmosphere. The smoke plume traveled northward along the Gulf coast and affected air quality extending well up into the midwestern United States. During the smoke event, according to the Texas Natural Resources Conservation Committee (TNRCC), the maximum PM measured in Brownsville, Texas, was 580 micrograms per cubic meter, almost four times the health-based NAAQS of 155 (*TNRCC 2000*). A survey conducted by the Texas Department of Health showed increased numbers of visits to doctor's offices and hospital emergency rooms for respiratory illnesses during the smoke event, mostly by patients with chronic, preexisting conditions (*TNRCC 1998*).

Another interaction between climate variability and biomass may be found in the release and dispersal of spores and pollen, which can act as allergens. Allergens are not criteria air pollutants but are included because of their temperature-dependent effect on air quality for allergic people. Pollen counts from birch trees (the main cause of seasonal allergies in northern Europe) seem to increase with increasing temperature (Ahlholm et al. 1998). Pollen counts for Japanese cedar significantly increase in years when summertime temperatures are unusually high (Takahashi et al. 1996; Tamura et al. 1997).

The Synergy between Heat Stress and Pollutants Affecting Health

The incidences of a range of illnesses are potentially associated with increases in temperature. Cardiovascular deaths are associated with temperature. The Chicago heat wave of July 1995 led to more than 700 excess deaths in the metropolitan area. In Athens, Greece, during a heat wave in 1987, the daily number of deaths increased by more than 40 when the mean 24-hour air temperature exceeded 30°C (Katsouyanni et al. 1993).

Mortality curves assume a classic J or V-shape, with highest mortality occurring at both high and low extremes of temperature. Generally, populations in warmer regions tend to be more vulnerable to cold (Eurowinter Group 1997), and those residing in cold climates are more sensitive to heat (Kalkstein and Greene 1997). In temperate regions, mortality rates are highest during the winter.

Physiological responses to both extreme heat and cold are not straightforward. For example, blood viscosity and cholesterol have been found to increase with high temperatures (Keating et al. 1986). On the other hand, blood pressure and fibrinogen levels increase during winter, although outdoor temperature does not seem to determine the seasonal variation of fibrinogen (van der Bom et al. 1997).

Climatologists project a doubling in the frequency of heat waves associated with a rise of 2–3°C in average summer temperature. A study of 44 U.S. cities found that, after adjusting for some expected acclimatization, heat-related mortality might increase by 70–150 percent (Kalkstein and Greene 1997). A meta-analysis of studies on 20 international cities, however, found a reduction in overall mortality due to fewer deaths during winter (Martens 1998).

Both heat waves and air pollution kill people. In addition to their individual effects, however, is there evidence for interaction between the effects of heat and air pollution? Recent studies have examined the health effects of exposure to extreme heat and air pollution to determine whether there are potential synergistic effects related to simultaneous exposure.

Katsouyanni et al. (1993) investigated the potential synergistic effects of air pollution and air temperature on excess mortality in Athens, Greece. The increased mortality during the major heat wave of July 1987 was compared to the number of deaths in July for the six previous years. There was a greater increase in the number of deaths in Athens (97%) during the July 1987 heat wave than in all other less polluted urban areas (33%) or in all nonurban areas (27%). The authors found interactions between high levels of air pollution and high temperature (30°C) that were statistically significant for SO_2 and suggestive for ozone and particulates.

Sartor et al. (1995) found that mortality during the Belgium heat wave of 1994 was higher than expected; an increase of 9.4 percent was observed among those younger than 65 years (236 excess deaths) and an increase of 13.2 percent was observed among those older than 65 years (1,168 excess deaths). Daily death figures were mostly correlated with mean daily temperature and 24-hour ozone concentration from the previous day. A synergistic interaction between the effects of temperature and ozone on mortality was determined across age groups and explained 39.5 percent of the variance for daily deaths for those over age 65. The authors concluded that elevated ambient temperatures combined with high concentrations of ozone were likely to have been responsible for the unexpected excess mortality.

These studies are far from conclusive, but other studies at least show seasonality in health effects. Sunyer et al. (1996) found that SO_2 in Barcelona, Spain, was associated with respiratory deaths in the summer; levels of ozone and NO_2 during the summer also positively correlated with cardiovascular mortality and mortality in the elderly population. On the other hand, Samet et al. (1998) found little evidence that weather conditions modified the effect of pollution. These interactions are methodologically difficult to study, but it will become increasingly important to determine whether there are any synergistic interactions between exposure to high temperatures and exposures to high levels of pollution.

Possible Pathways of the Effect of Global Climate Change on Public Health

Although the focus of this chapter has been on global climate change and air pollution, it is important to recognize that the potential health effects of global climate change go far beyond adverse effects of air pollution. Global climate change may affect human health via multiple pathways (Fig. 13.3). Further, the dynamics of global climate change occur in a broader context of the interplay between natural and anthropogenic forces in our global ecosystem that are changing how land, water, air, and energy are used. As such, an exploration of the possible pathways by which global climate change affects public health appears in multiple contexts throughout this book. Illustrations of these pathways selected from this book are discussed below. More in-depth reviews on this subject can be found in the literature (Strzepek and Smith 1995; McMichael et al. 1996; Patz et al. 1996; Patz 1998; World Health Organization 1996).

The Rise in Temperature

One of the main expectations of global climate change is a rise in global mean temperature (Chapter 7). Therefore, one of the priorities for understanding the health consequences of global climate change is an assessment of health problems that will grow worse as temperature increases. Under warmer conditions, the rate of heat-related fatalities is likely to grow, especially among elderly populations (see "The Synergy between Heat Stress and Pollutants Affecting Health," above). Increasing heat may exacerbate the effects of conventional air pollutants, most notably ground-level ozone, as described under "The Influence of Weather on Ozone Formation" (above). Increased heat may also lead to greater problems with allergies to spores and pollen (see "Climate Variability, Biomass, Air Quality, and Health: Forest Fires and Allergens," above).

The quality of food may also deteriorate. For example, cholera, which is an infectious disease that may be transmitted through food, seems to be more frequently transmitted at warmer temperatures (see Chapters 10 and 11). In addition, temperature is a critical factor in the cycle of transmission of many parasitic diseases. For example, the parasite that causes malaria is transmitted from person to person by the bite of a mosquito; both the survival of the mosquito vector and the development of the parasite within the mosquito vector depend on temperature (see Chapters 10 and 12). In

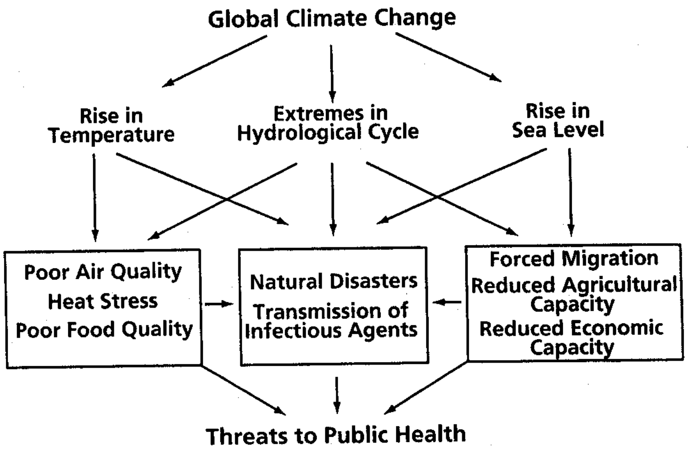

Figure 13.3 Linkages between global climate change and threats to public health.

many cooler settings at higher latitudes and higher altitudes, an increase in temperature could affect the chance of transmission. Similar arguments apply to insect pests and plant pathogens that affect agricultural crops (see Chapter 10).

Extremes in the Hydrological Cycle

Another major concern about the effects of global climate change is an increase in the frequency of extremes in the hydrological cycle, that is, more floods and more droughts (see Chapters 7 and 9). Extreme flooding has direct effects on people as a natural disaster, causing accidental deaths (e.g., drowning, burial in mudslides) and forcing people from their homes (see Chapter 14). Flooding also has less direct effects through an increase in the incidence of some infectious diseases, such as leptospirosis (see Chapter 14).

Increased rainfall can affect the incidence of infectious diseases through changes in wildlife populations that are the reservoirs of infection. For example, hantavirus pulmonary syndrome in the southwestern United States is transmitted by a virus circulating in rodent populations whose numbers increase during unusually wet periods (Glass et al. 2000) because of abundant growth of the vegetation that provides a source of food (see Chapters 2 and 10).

Droughts, at the other extreme, can lead to the loss of agricultural productivity and contribute to the forced migration of people from rural areas (see Chapter 6). Forced migration for whatever reason can result in refugee camps with extreme health problems, including waterborne diseases (see Chapters 6 and 14).

Shortages of water because of diversion also provide evidence of the possible effects of droughts on health. The system for distributing drinking water in Nukus, Uzbekistan, in the Aral Sea basin was made more vulnerable to biological contamination because of low pressure in the pipes, which in turn was due to the diversion of water to irrigate cotton fields (see Chapter 14). Diversion of water for cotton fields has also been responsible for shrinkage of the Aral Sea, which has increased the number of dust storms in the region (see Chapter 14). On a smaller scale, the diversion of water from lakes in California to support the metropolitan growth of Los Angeles has increased the dustiness of the air in violation of U.S. standards for air quality (see Chapter 14).

The Rise in Sea Level

The third major physical effect of global climate change is a global rise in sea level (Chapter 7), a process that has been evident over the past century (Chapter 9). A rise in sea level could inundate land and contaminate freshwater aquifers with seawater, leading to the forced migration of populations as well as reductions in agricultural and economic activity (see Chapter 9). As noted under "Extremes in the Hydrological Cycle" (above), forced migration itself can lead to a variety of serious health problems (see Chapters 6 and 14). A rise in sea level can also increase the risk of flooding and hence all of the health consequences associated with floods.

The Relationship with Stratospheric Ozone Depletion

Global warming at the earth's surface is associated with a cooling of the stratosphere, which tends at high latitudes to accelerate the destruction of stratospheric ozone that protects the earth from excessive ultraviolet-B (UV-B) radiation (Chapter 7) (Shindell et al. 1998). The relationship is due to intrinsic physical characteristics of the flow of energy and does not depend on whether the cause of global warming is natural or anthropogenic.

Studies of the health effects of global climate change have focused on the effects of a rise in temperature, extremes in the hydrological cycle, and a rise in sea level (see Fig. 13.3). Studies of the health effects of stratospheric ozone depletion have focused on the effect of UV-B radiation on various organs, especially skin, eyes, and the immune system (see Chapter 7). Consideration of illnesses induced by UV-B can deepen an appreciation for the relationship between global warming and stratospheric ozone depletion, but including these illnesses in a total accounting of global climate change can also foster confusion. Stratospheric ozone depletion occurs because many industrial chemicals act directly to break down stratospheric ozone and is not simply a consequence of global warming.

Conclusion

This chapter has contrasted the ramifications of increases in greenhouse gas emissions against the backdrop of improving trends in conventional air pollution in North America. Greenhouse gas emissions causing climate change have emerged as a new air pollution problem with direct and indirect health implications. Classical urban air pollution problems still plague much of the developing world. In developed countries with cleaner air, climate change has the potential, because of the effects of temperature and weather conditions on the formation and transport of air pollution, to reverse some of the gains achieved in air quality.

We discussed four key themes in this chapter:

1. Historically, air pollution problems and their remediation have generally diffused local hazards into more regional and now global distributions.
2. Fossil fuel use is a major source of both conventional air pollutants (criteria pollutants in EPA terminology) and greenhouse gases, such as CO_2.
3. As a "secondary" air pollutant, regional ozone formation and transport is influenced by climatic factors, such as temperature, wind, and UV radiation. Ozone, or "photochemical smog," remains a pervasive problem in North America, which may be exacerbated by future global warming or stratospheric ozone depletion.
4. Global climate change may affect public health through a diversity of pathways, including heat waves, air pollution (especially ozone), vector- and waterborne diseases, and sea level rise or weather extremes that could alter agriculture and water supplies or displace human populations.

SUGGESTED STUDY PROJECTS

Suggested study projects provide a set of options for individual or team projects that will enhance interactivity and communication among course participants (see Appendix A). The Resource Center (see Appendix B) and references in all of the chapters provide starting points for inquiries. The process of finding and evaluating sources of information should be based on the principles of information literacy applied to the Internet environment (see Appendix A).

PROJECT 1: Global Climate Change and Air Pollution

The objective of this project is to demonstrate an understanding of aspects of the relationships between global climate change and air pollution.

Task 1. Describe the key sources of greenhouse gases, criteria air pollutants, and air toxics in the United States.

Task 2. Describe the evidence linking increased temperatures to higher concentrations of ground-level ozone.

Task 3. Describe projections of the effects of global climate change on ground-level ozone.

PROJECT 2: Unintended Consequences of Programs to Control Harmful Emissions

The objective of this project is to demonstrate an understanding of how programs to control harmful emissions may cause unintended environmental health problems.

Task 1. Select a historical, current, or projected program for controlling harmful emissions (e.g., hydrocarbons, acid rain).

Task 2. Describe the benefits and unintended negative consequences (realized or potential) for human health and the environment.

PROJECT 3: Possible Pathways of the Effect of Global Climate Change on Public Health

The objective of this project is to demonstrate an understanding of the possible pathways of the effect of global climate change on public health.

Task 1. Select two or more linkages in the possible pathways of the effect of global climate change on public health (see Fig. 13.3) and find examples of each. At least one example of each linkage must be found in the literature outside of this book.

Task 2. Select two or more geographic areas. For each area, identify the possible pathways of the effect of global climate change that are most relevant to the population in that area.

Task 3. For each geographic area selected in task 2, describe other environmental changes that could interact with the possible pathways of the effect of global climate change in that area.

Task 4. Summarize your results.

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