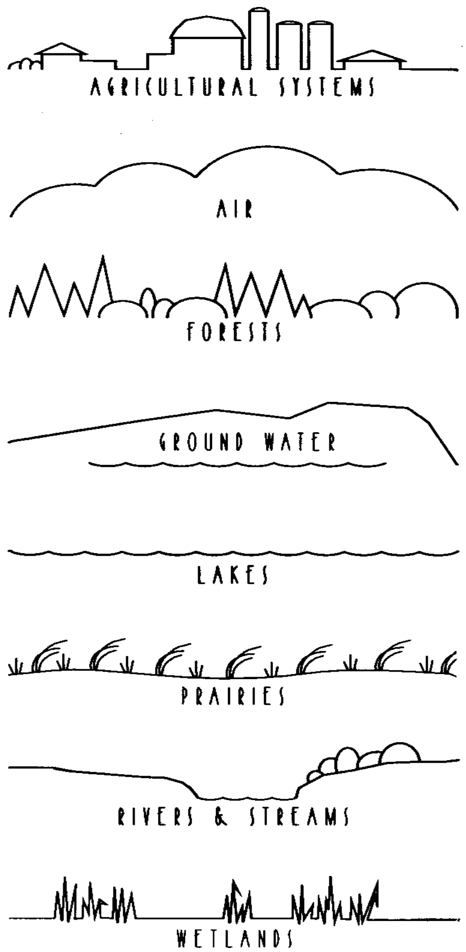
DEVELOPING ENVIRONMENTAL INDICATORS FOR MINNESOTA



Atmosphere

The Environmental Indicators Initiative

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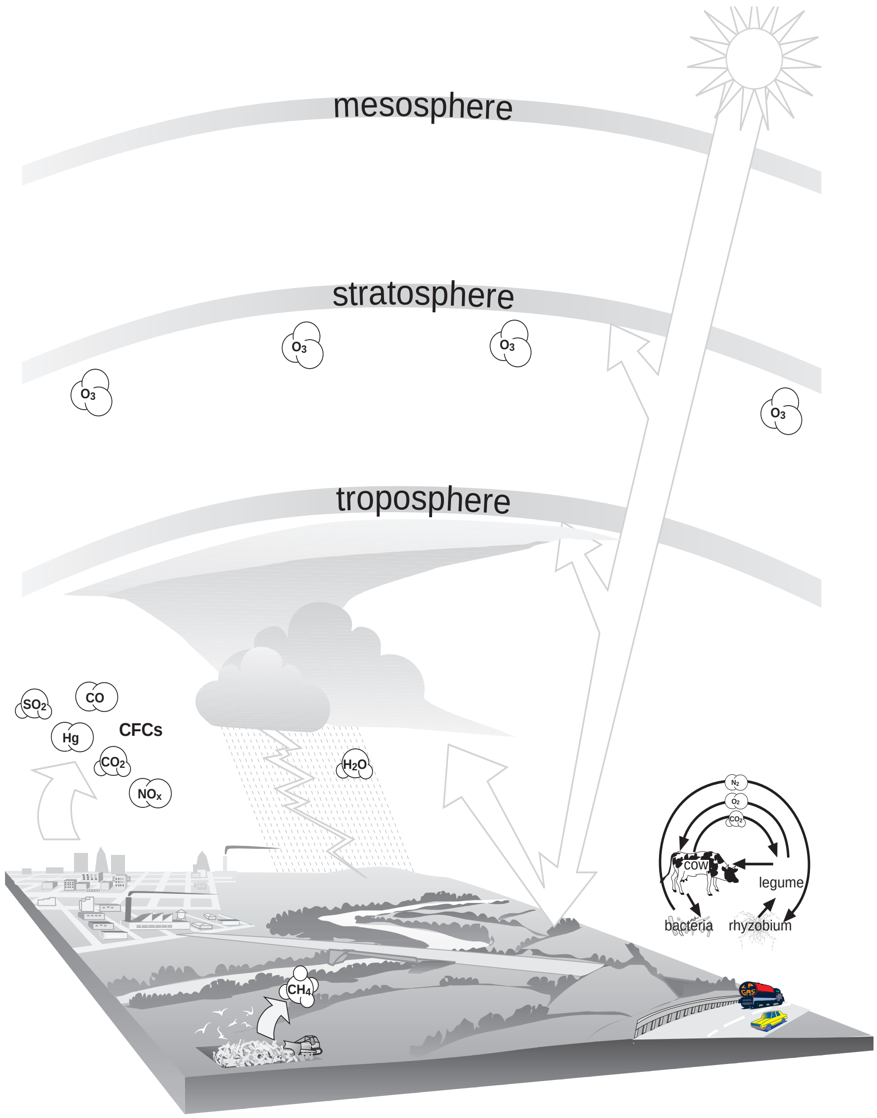


Citizens and decision makers use environmental indicators to help effectively manage and protect Minnesota's air. Environmental indicators answer four questions.

What is happening to our atmosphere?

Environmental condition can be assessed using indicators based on characteristics of the atmosphere, including **concentrations of various airborne pollutants**, the **area and percentage of forest land affected by ground-level ozone pollution**, the **extent of thinning of the protective ozone layer in the upper atmosphere**, and the **concentration of carbon dioxide and other greenhouse gases** that may cause global warming.

Why is it happening?

Indicators of *human activities* that affect the atmosphere include the **number of permits issued for facilities that pollute the air**, the **percentage of electricity generated by burning coal or other fossil fuels**, the **number of automobiles on the road**, and the **percentage of solid waste disposed of by incineration**.

How does it affect us?

Changes in air quality may diminish the flow of *benefits* we derive from a clean atmosphere. Indicators of how we are affected include the **number of new asthma cases**, the **number of lakes having fish-consumption advisories** based on airborne toxic chemicals, the **amount of harmful ultraviolet radiation**, and the **number of people living in areas where pollution regularly exceeds air-quality standards**.

What are we doing about it?

Societal strategies to maintain or restore air quality include **pollution-control technologies** (such as stack scrubbers on coal-fired power plants and catalytic converters on automobile engines), **reductions in the use of chemicals that cause thinning of the protective ozone layer**, and **reductions in emissions of carbon dioxide**.

In this chapter we outline the benefits of a clean atmosphere, the key characteristics that determine the health of the atmosphere, the pressures affecting the atmosphere today, and the most significant of Minnesota's policies and programs that affect the atmosphere.

ATMOSPHERE

EII

HIGHLIGHTS

Benefits of a Healthy Atmosphere

- Livable temperatures
- Protection from harmful ultraviolet radiation
- Lower rates of respiratory ailments
- Cycling of nutrients essential for plant and animal growth
- Pollination of crops and other plant species
- Precipitation
- Wind energy

Important Atmospheric Characteristics

- Stratospheric ozone intercepts ultraviolet radiation.
- Uneven heating of the earth's surface generates weather phenomena and climate patterns.
- Greenhouse gases maintain livable temperatures.
- The atmosphere is a major reservoir for carbon, nitrogen, oxygen and water.

Pressures on Air Resources

- Release of carbon dioxide and other greenhouse gases from industrial and agricultural activities, energy production, and automobiles
- Heat islands in urban areas
- Emission of persistent toxic substances, particulate matter, and acid-forming compounds
- Depletion of stratospheric ozone by chlorofluorocarbons
- Formation of ground-level ozone

Status and Trends

- Approximately 70% of pollution emitters are regulated by the MPCA
- Mercury deposition has decreased since 1970 in some areas of the state

Existing Policies and Programs

- Air-quality standards and emission regulations that meet the needs of the state

HOW WE BENEFIT FROM A HEALTHY ATMOSPHERE

The atmosphere seems endless, but it is no more than a thin skin wrapped around the earth's surface. All living things depend on the atmosphere. Green plants and algae use sunlight to combine atmospheric carbon with water to produce carbohydrates, the basic fuel of life. As they photosynthesize, green plants and algae release oxygen into the atmosphere, and it is this oxygen that is critical to the survival of nearly all of earth's organisms.

The atmosphere sustains conditions on earth that allow living organisms to survive. For example, naturally occurring greenhouse gases (carbon dioxide and water vapor) allow solar energy to enter the earth's atmosphere but slow its return to space. The result is an average surface temperature of about 15°C. Without the greenhouse effect of the atmosphere, the earth's average temperature would fall to -20°C, much too cold to support life as we know it. Ozone high in the stratosphere protects living organisms by absorbing most of the sun's harmful ultraviolet wavelengths, which cause skin cancer and eye disease, and damage crops, other plants, and immune systems. The vast majority of meteorites moving toward the earth's surface burn up harmlessly in the atmosphere instead of creating craters like those characteristic of the moon.

A clean atmosphere is essential for human health. We inhale about six liters of air every minute. Polluted air can initiate asthma attacks, irritate throats, eyes, and lungs, and cause chronic lung disease and emphysema (MEQB 1988). In the worst cases, smog-prone cities issue pollution alerts to warn their citizens to stay indoors when pollution levels are high. Children, the elderly, and people with heart disease are among those most susceptible to the ill effects of polluted air (MEQB 1988).

The atmosphere plays a key role in distributing and cycling the elements essential for life, such as carbon and nitrogen, and water. These nutrients cycle between the atmosphere and the tissues of plants and animals. They are assimilated into soils as plant and animal remains decompose, and return to the atmosphere as gases.

Finally, our atmosphere is a physical force in every ecosystem. Erosion of landscapes through the action of wind and wind-induced waves has shaped the earth throughout its history, creating places of beauty as well as harsh, infertile landscapes. Winds transport pollen, seeds, bacteria, spores, and dust far from their points of origin. Wheat, corn, rice, and many other crop plants and trees depend on wind for pollination. The atmosphere receives water vapor from water bodies and transpiring plants and redistributes it as rain and snow. The atmosphere also dilutes pollutants released from point sources.

In the following pages we describe the atmosphere and the pressures we exert on it, and give information regarding the current state of our atmosphere. This information is critical to developing a comprehensive set of indicators for monitoring the atmosphere and the human, terrestrial, and aquatic systems to which it is linked.

CHARACTERISTICS OF THE ATMOSPHERE

Earth's earliest atmosphere was mostly nitrogen, methane, and carbon dioxide, with little oxygen. The first living organisms, probably similar to today's anaerobic bacteria, were adapted to this atmosphere. Evolution of the atmosphere we know today began about 3.5 billion years ago with the first additions of free oxygen from early photosynthesis. Single-celled blue-green algae used carbon dioxide and emitted oxygen as a by-product, slowly increasing the free oxygen that could support more complex forms of life, and also allowing the development of a protective layer of ozone in the stratosphere. Over time, the action of living creatures increased oxygen and removed heat-trapping carbon dioxide from the atmosphere. With these changes, the earth's environment became increasingly more like it is today. Although the composition of the atmosphere has changed continually through the earth's history, it has remained fairly stable for the past 10,000 years.

Today's atmosphere is about 78 percent nitrogen and 21 percent oxygen, with smaller amounts of water vapor (about 3 percent), argon (1 percent), and carbon dioxide (0.035 percent) (Miller 1991). The atmosphere consists of several layers resulting from changes in temperature and in concentrations of gases. About 80 percent of the mass of the atmosphere lies within the troposphere, the lowest layer of the atmosphere. It is in this layer, 6 to 17 km thick, that clouds, surface winds, water vapor, and many pollutants circulate around the planet. Another 19 percent of the mass of the atmosphere lies in the stratosphere, which extends to 50 km above the earth's surface. Within this zone ozone absorbs ultraviolet radiation. The last two layers, the mesosphere and the thermosphere, are only 1 percent of the atmosphere's mass but reach out several hundred kilometers into space.

Uneven heating of the earth's surface and the atmosphere creates winds and generates precipitation. The equatorial regions receive more direct sunlight and accumulate more heat than do the polar regions. Warm, less dense air at the equator moves upward and poleward, pushing cool, denser air from the poles toward the equator. As warm air moves upward, the water it holds condenses, forming clouds and eventually falling as precipitation. The earth's rotation bends some of these masses of rising and falling air into major air currents, such as the jet stream, which are more or less permanent features of the middle atmosphere.

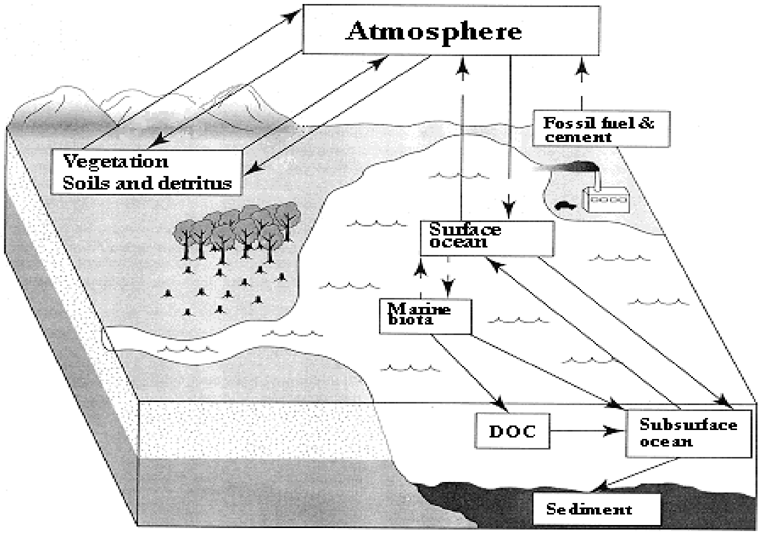
Air movement is also affected by mountains and other major land features, which divert air masses horizontally and vertically. In North America, for example, warm air moving northward from the Gulf of Mexico often moves unobstructed into Minnesota. On the other hand, air moving from the Pacific Ocean is usually diverted upward by the Sierra Nevada and the Rocky Mountains. As it rises, the air cools and the moisture in it condenses to form rainfall on the west side of the mountains. Only a small portion of this air and precipitation reaches Minnesota.

Around the world we see dramatic examples of atmospheric forces, including the monsoons of India, the large desert regions of the world, the torrential tropical rains of the Amazon, and the powerful hurricanes in the southeast United States. These and other regional climate patterns help define the culture of an area. Clothing, architecture, agriculture, recreation, economic activities, and cultural activities are all tightly linked to climatic patterns determined by dynamic processes in our atmosphere.

Humans have dramatically influenced atmospheric chemistry at both local and global scales, and we are only beginning to understand the implications of those alterations. Pollutants are only a small percentage of the atmosphere but have disproportionately large effects on human health and ecosystem function. While natural changes to the atmosphere have occurred since the beginning of the earth's history, they have occurred much more slowly than those we are currently experiencing. The unprecedented rates of change present a unique and pressing challenge for humans.

Figure 1

Global Carbon Cycle



PRESSURES ON THE ATMOSPHERE

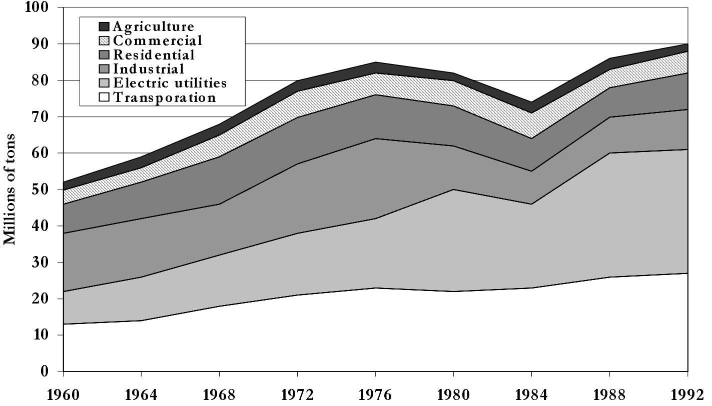
During the earth's 4-billion-year history, volcanoes spewed aerosols and gases into the troposphere and stratosphere, changes in orbit and orientation altered weather and climate patterns, and plant and animals influenced concentrations of carbon dioxide and methane gas in the air (Berger 1977; Houghton et al. 1992). Such changes occurred gradually, over hundreds or thousands of years. Organisms and ecosystems had time to adjust to the changes. In the past 200 years, however, industrialization and dramatic human population growth have put significant new pressures on the atmosphere: **large-scale alteration of natural ecosystems**, **construction and expansion of urban environments**, and pollution.

The atmosphere is a major reservoir of the carbon that is essential for life (Figure 1). Carbon dioxide gas helps keep the earth at a temperature hospitable to life. Plants remove carbon dioxide from the air via photosynthesis to build the carbohydrates that support all organisms. Proteins, carbohydrates, and the other chemicals that make up living tissue are built around skeletons of carbon molecules.

Many human activities affect the amount of carbon stored in the atmosphere. Worldwide, about 700 billion tons of carbon dioxide enters the atmosphere each year from natural processes, and about 700 billion tons are absorbed again by other natural processes. Over the past several hundred years, however, increases in the amount of carbon in the atmosphere have resulted from human activity. We now add about 24 billion additional tons of carbon dioxide to the atmosphere annually (Morrisey and Justus 1998). Mining limestone for construction and burning fossil fuels add large amounts of carbon to the atmosphere. More recently, extensive conversion of natural habitats to agriculture and urban lands also has increased the amount of carbon in the atmosphere. As soils are plowed, peat is mined and burned, and trees are cut and burned, the carbon that was held in those reservoirs enters the atmosphere. As agriculture expands to feed burgeoning human populations, paddy rice farming and cattle raising will add substantial

Figure 2

CO_2 Production from Fossil Fuel Combustion in Minnesota



amounts of carbon (as methane) to the atmosphere. The additional carbon dioxide and methane may increase the greenhouse effect of the atmosphere (Houghton et al. 1992, 1995) and throw climate, weather, and other cycles out of balance.

In Minnesota, the primary source of the carbon dioxide released to the atmosphere is the combustion of petroleum, coal, and natural gas. Since 1960, transportation and electric generation has accounted for most of the carbon dioxide emissions in the state (Figure 2).

The atmosphere is also a major reservoir of the nitrogen that is essential for life (Figure 3). Most of this nitrogen is unavailable for use by living organisms until bacteria that live symbiotically with plants (primarily legumes) and in soils and a few species of algae convert nitrogen gas to chemical forms that can be used by other organisms. The amount of nitrogen made available in this way is a very small but vital portion of the total nitrogen available to living organisms. But large quantities of nitrogen in forms that can be used directly by plants are released to the atmosphere when fossil fuels are burned. This excess nitrogen, distributed worldwide by the atmosphere, may have serious impacts on many ecosystems because of the role that nitrogen limitation plays in organizing and maintaining living systems. One anticipated consequence of **increased nitrogen availability due to deposition** from the atmosphere is the loss of biological diversity, especially among plants adapted to low-nitrogen soils (Vitousek et al. 1997).

Urbanization

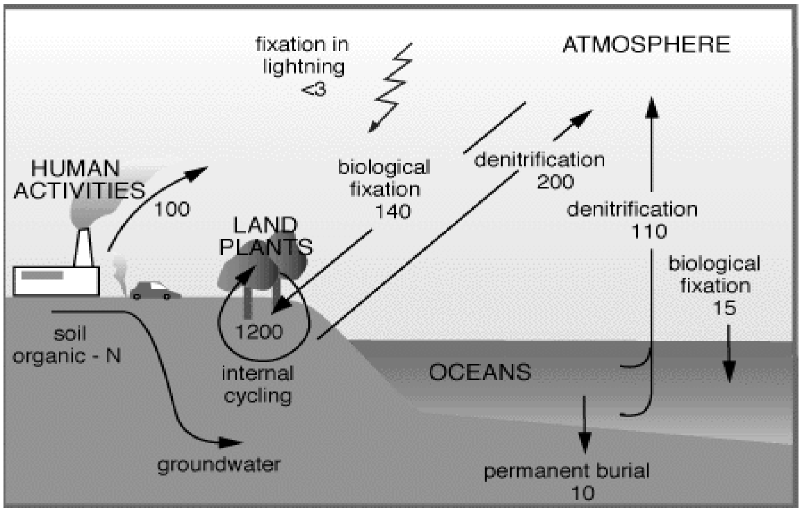
Over 70 percent of the U.S. population lives in urban areas, and it is projected that by the year 2005 urban centers will be home for more than 50 percent of the world's population (Brown et al. 1996). Urbanization has significant effects on the atmosphere, especially on local heat balances. Asphalt and concrete absorb large quantities of solar energy and reradiate it to the surrounding air. Vehicles, apartments, and offices lose heat to the atmosphere. In addition, some of the pollutants common in urban areas (discussed in more detail later) are effective at trapping heat. As a consequence, urban areas become islands of heat compared to nearby rural areas.

The **elevation of temperatures in urban centers** has important implications for air quality. Common urban pollutants, such as nitrous oxides and volatile organic compounds, combine in the presence of elevated temperatures and direct sunlight to form smog and ground-level ozone. When air is stagnant for several days and these compounds accumulate, the health of people exposed to them can be compromised.

The intensity of the urban heat island effect depends on the extent of urbanization, the local topography, the nature of the pollutants occurring in the area, and local weather conditions (Government of Canada 1991). For example, winds may carry pollutants away from the city, reducing their local impact but contributing to regional pollution problems. Mountains or other topographic barriers may prevent the dispersal of pollutants and allow pollutant concentrations to build to toxic levels.

Figure 3

Global Nitrogen Cycle



The urban heat island phenomenon can be moderated by many practices. Using light-colored concrete and roofing materials that reflect more light in place of asphalt and tar paper helps keep the urban environment cooler. Trees cool the city by absorbing sunlight and providing shade (Chen 1997). These and similar mitigation strategies could save $10 billion to $15 billion annually by reducing cooling costs and reducing smog-related health problems (Stetson and Koedijk 1996).

Pollution

Many human activities contribute to pollution, including industrial activities, the burning of fossil fuels, and mining and farming practices that introduce fine dust particles into the atmosphere. Pollutants are emitted by mobile, industrial, and area sources (MPCA 1997a; Table 1). Mobile pollution sources include vehicles and machines that burn fossil fuels, including cars and airplanes. Industrial sources, often called point sources, are large stationary sources such as factories, refineries, and power plants. Area sources are small, widely distributed, stationary sources such as home furnaces and restaurant kitchens. In the recent past, greater attention was directed toward controlling point sources of pollution (e.g., factories, refineries) than other sources of pollution. Today **pollution-reduction regulations** also control nonpoint and area sources.

GLOBAL ATMOSPHERE ISSUES

Climate change

Climate change is the cumulative change in temperature and climate patterns resulting from increases in the atmospheric concentration of greenhouse gases from anthropogenic and other sources (Figure 4). The earth retains heat due to the presence of greenhouse gases (e.g., carbon dioxide, methane, water vapor) in the atmosphere, a phenomenon that is essential for maintaining conditions suitable for life. However, some human activities, such as burning fossil fuels, deforestation, large-scale cattle raising, and paddy rice agriculture are rapidly increasing the **concentration of greenhouse gases** in the atmosphere. This increase may cause dramatic changes in climate over a much shorter time than ever before. Rapid climate change on a global scale would have massive effects on the earth's weather, agricultural systems, native ecosystems, and natural preserves (Miller 1991).

Since the Industrial Revolution, the burning of fossil fuels has pumped

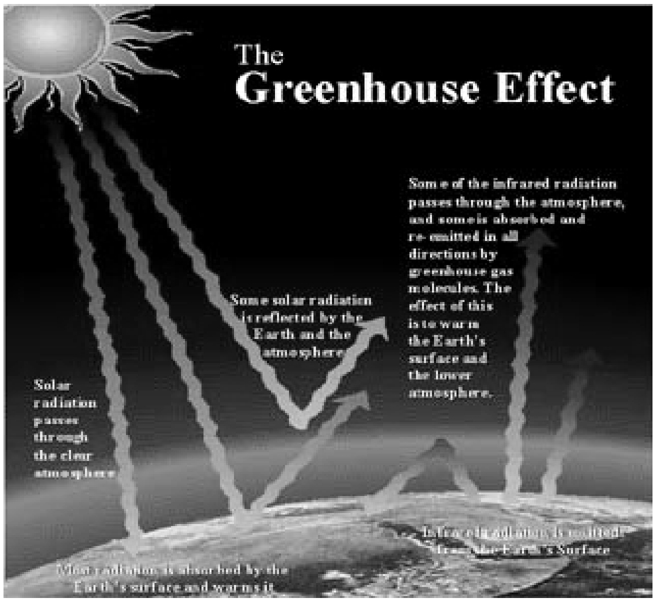
Table 1

Sources of Important Pollutants

Pollutant	Mobile source	Industrial sources	Area sources
Smog-forming chemicals	45%	31%	24%
Particulates	15	60	25
Urban toxic substances (e.g., benzene)	64	1	35
Mercury	0	65	35
Acid rain-forming compounds	5	91	4
Ozone-depleting compounds	18	5	77
Greenhouse gases	36	48	16

Figure 4

The Greenhouse Effect



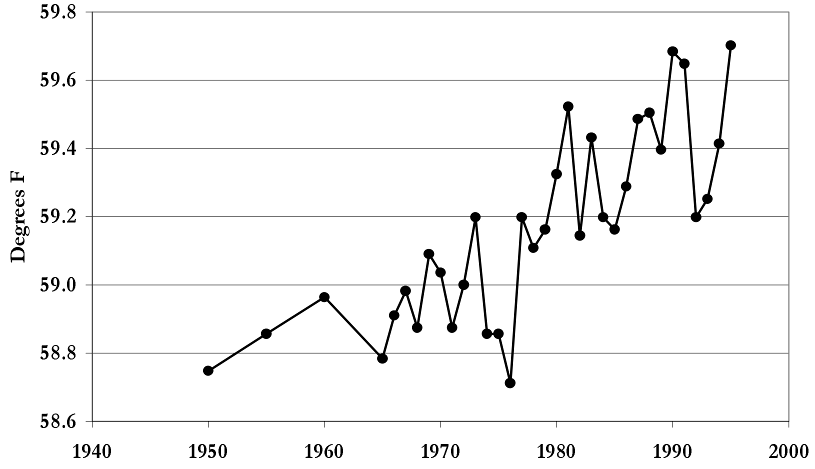
massive amounts of carbon dioxide into the atmosphere. Human activity adds about 24 billion tons of carbon dioxide to the atmosphere annually (Morrisey and Justus 1998). An average American automobile, driven about 10,000 miles per year, releases its own weight of carbon into the atmosphere (Miller 1991).

The increase in atmospheric carbon dioxide accounts for 60 percent to 70 percent of the observed greenhouse effect (MPCA 1997a). One molecule of methane, however, is about 25 times more effective at retaining heat than is a molecule of carbon dioxide (Miller 1991), and small increases in methane concentrations may result in large changes in heat retention. Rice paddy agriculture and large-scale cattle raising are significant sources of methane (Houghton et al. 1992, 1995), and these sources may increase as the world population increases.

Global average temperatures have risen 0.6° to 1.2°F since the late 1800s (US EPA 1997), and climate scientists expect additional increases of 2° to 5°F during the next century as carbon dioxide levels rise (Figure 5; MPCA 1997a). Warmer temperatures may have profound effects on global weather patterns, creating violent storms and disrupting rainfall patterns. The polar ice caps may melt, raising sea levels enough to flood island nations and low-lying continental coasts. Global warming may also disrupt ecosystems and lead to the extinction of species. The unprecedented speed of this human-caused change would have serious implications for the survival of other species. Plants and animals that once had thousands of years to migrate or adjust as climate changed may now be caught in a rapid warming trend for which evolution has not prepared them (Halpin 1997). Natural preserves, set aside as refuges for wild species, may become unsuitable habitat as the climate changes, for example, wetlands could turn to dry meadows, and savannah ecosystems could convert to deserts. Species surviving in park island ecosystems may find themselves with nowhere to go.

Figure 5

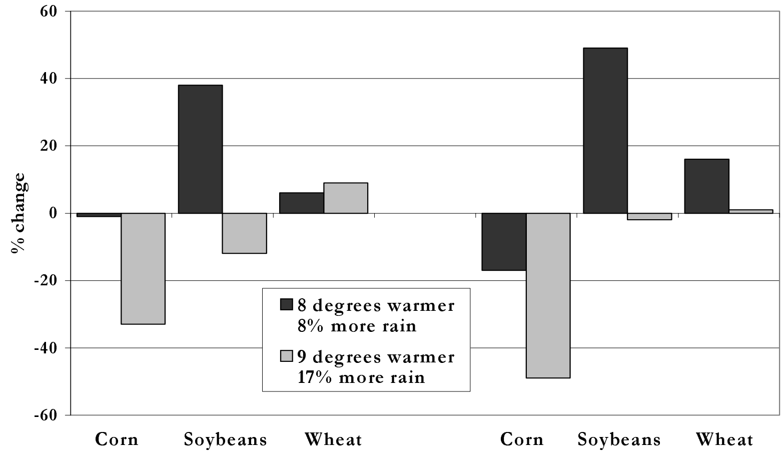
Average Temperature of the Earth Surface



While global warming is not yet incontrovertibly confirmed, evidence continues to mount that the global climate is becoming warmer and more violent. The effects of global climate change on any particular region are hard to predict, though we can make some educated guesses. Here in Minnesota, **average rainfall** in the state has increased over the past century, rising as much as 20 percent in the southern half of the state. Average annual temperatures in Minneapolis have increased from 43.9°F (average for 1888-1917) to 44.9°F (average for 1963-1992; US EPA 1998). Some models predict that if alteration of the global atmosphere continues, Minnesota's **average annual temperature** could rise by about 4°F by 2100, with hotter summers and, most likely, increased rainfall.

A warmer, wetter climate would affect all of Minnesota's ecosystems and its citizens. Without severe winters, mosquitoes that carry yellow fever, dengue fever, eastern equine encephalitis, and LaCrosse encephalitis could survive in our state (they already breed as far north as Chicago). Certain agricultural pests might also increase in a warmer, wetter climate. While warmer

Figure 6
Potential Climate Change Effects on Agriculture

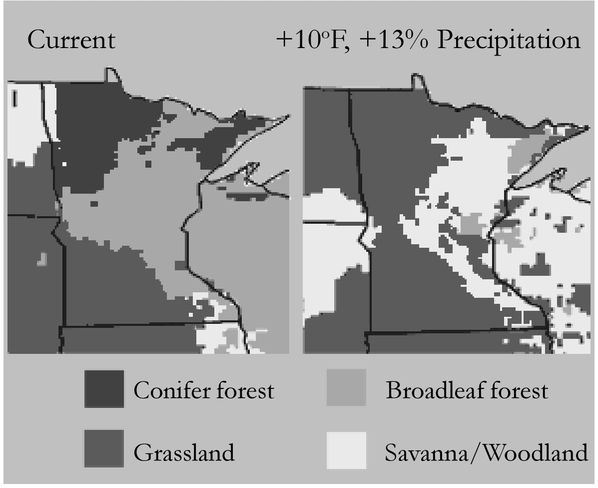


temperatures could expand the range of many crops northward, soils in the northern part of the state are not well suited to agriculture. Yields of soybeans and wheat in current agricultural areas are likely to increase under expected temperature and precipitation regimes, while yields of corn would likely decrease (Figure 6).

Trees and forests adapted to specific climate conditions are likely to change as climate changes. Under warmer, wetter conditions, our northern forests might be replaced by a more southerly mix of oak and southern pines (Figure 7; US EPA 1998). If the climate warms but also becomes drier, both hardwood and conifer forests could be replaced by prairie and savannah ecosystems. Wildlife species and economic activities also would need to accommodate the changed conditions.

Lakes, rivers, and wetlands would be affected in several ways. **Stream flows** could peak sooner in the spring because of earlier snowmelt and ice breakup (US EPA 1998). This could mean reduced stream flows in summer, decreased water quality, and reductions in fish habitat. Warmer **lake temperatures** may affect fish communities, favoring some species and stressing others.

Figure 7
Changes in Forest Cover



While a warmer climate would mean a longer ice-free shipping season for the Mississippi River and Lake Superior, increased evaporation and lower water elevations could make shorelines more susceptible to damage by wind and rain erosion. A warmer climate could dry many of the state's wetlands, including the prairie potholes that are the continent's single most important breeding ground for waterfowl such as mallards, pintails, and blue-winged teal (US EPA 1998).

Best estimates suggest that stabilizing global temperatures would require a 60 to 80 percent reduction in **emissions of greenhouse gases** worldwide (MPCA 1997a). Industrial nations account for most emissions of greenhouse gases, particularly carbon dioxide. The United States, the largest single contributor, emitted 1.4 billion tons of the 6.1 billion tons emitted worldwide in 1995 (Brown et al. 1996) and also has the world's highest **per-capita emission** rate, at

5.25 tons of carbon per person each year. It is difficult and expensive to remove the carbon dioxide from exhaust gases and nearly impossible to trap carbon dioxide from many other sources. Strategies for reducing carbon dioxide emissions concentrate on **reducing the use of fossil fuels** through conservation, energy efficiency, and reliance on alternate energy sources, including solar and nuclear power. Since trees absorb carbon dioxide and store the carbon for long periods, **reforestation** and **urban tree planting** can help offset increases in atmospheric carbon dioxide (Morrisey and Justus 1998).

Under the 1997 Kyoto Protocol, the United States has agreed to stabilize its greenhouse gas emissions at 1990 levels by the year 2000. However, emissions have not been stabilized, and it is unlikely that the United States will meet its treaty obligations (MPCA 1997a). Despite such setbacks, negotiations continue on other international agreements to limit emissions of greenhouse gases. Reducing the threat of global warming will require international cooperation and coordination of policies between industrial and industrializing nations.

Ozone depletion

About 90 percent of a**tmospheric ozone** is in the stratosphere, where it absorbs 99 percent of high-energy ultraviolet radiation from the sun (Miller 1991). The protection afforded by ozone is vital to life on earth, as ultraviolet radiation damages living tissue, causing skin cancer, cataracts, and many other disorders. Since the early 1980s, scientists have noted a thinning of the ozone layer, especially above the North and South Poles.

Ozone thinning is caused by long-lasting industrial chemicals that travel to the upper atmosphere and interfere with ozone formation. These chemicals include chlorofluorocarbons, halon compounds, and solvents such as carbon tetrachloride. Chlorofluorocarbons and halons are nontoxic and unreactive at ground level but interrupt ozone formation when energized by high-altitude sunlight. Chlorofluorocarbons, or CFCs, are widely used as refrigerants and aerosol propellants.

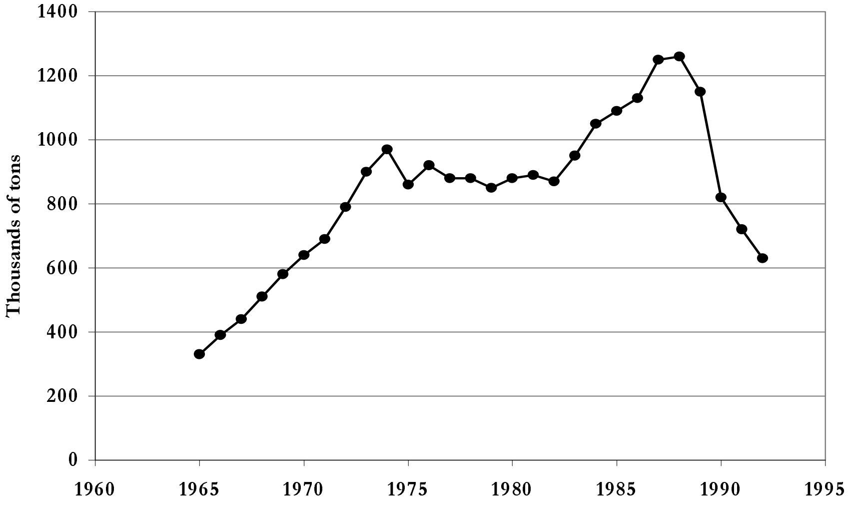
As much as 60 percent of the stratospheric ozone may disappear as winter air currents trap CFCs above the poles (Steer et al. 1992; Brown et al. 1996). The annual spring breakup of the Antarctic air vortex sends masses of ozone-depleted air over Australia and other populated areas. In these areas, levels of ultraviolet radiation may increase by as much as 20 percent (Miller 1991). A NASA study revealed that ozone declined by 3 percent over the Northern Hemisphere between 1969 and 1988 (Miller 1991). In parts of the middle latitudes, ozone was reduced by 10 percent during the spring of 1995 (Brown et al. 1996).

As ozone thins, more ultraviolet radiation reaches the earth. Each 1 percent loss of ozone leads to an increase of about 2 percent in the amount of ultraviolet radiation that reaches the earth's surface and an increase of 5 to 7 percent in skin cancer cases. The **rate of damage to the genetic material of humans and other organisms** and **incidences of skin cancer, eye cancer, cataracts, and immune-system disorders** (Miller 1991) may increase. Amphibians, with their thin skins and jelly-coated eggs, may be particularly vulnerable to damage from ultraviolet light (Blaustein 1994). Many plants, including important tree and crop species, suffer leaf damage and reduced growth as ultraviolet light increases.

Global efforts to reduce **emissions of ozone-depleting chemicals** have resulted in several international agreements. Under the 1987 Montreal Protocol, 49 nations agreed to reduce production of the 8 most widely used CFCs. The 1989 Helsinki Agreement requires 82 countries to phase out use of the 5 most damaging CFCs by the year 2000, if substitutes are available by then. However, putting these principles into action has been slow, and worldwide commitment to ozone layer protection has been spotty. While **consumption of CFCs** in industrial countries decreased by 74 percent from 1986 to 1993, consumption in developing countries increased by 40 percent during the same period. As large nations such as China and India seek more affluent lifestyles, use of CFCs (particularly as refrigerator coolant) may increase dramatically. In the United States the largest single contributor to CFC emissions is leakage from automobile air conditioners (Miller 1991). The damage these chemicals cause is long-term and expensive; one study estimates that the CFCs released from one average aerosol can will cause $12,000 worth of damage over the life of the chemicals (Miller 1991). **CFC production** peaked in 1989 and has dropped to pre-1970 levels (Figure 8; Brown et al. 1986), but because CFCs and other ozone-depleting chemicals can linger in the atmosphere for decades, even an immediate, total ban would not restore the ozone to previous conditions for about 100 years (Miller 1991).

Figure 8

Global CFC Production



TRENDS IN AIR POLLUTION

Minnesota has a strong and successful regulatory process, credited for significantly reducing certain pollutants in recent years. Levels of most major industrial air pollutants have decreased since 1971. Regulations have led to much better control of point-source pollution and to reductions or leveling off in **emissions of sulfur dioxide, ozone, volatile organic compounds, lead, and carbon monoxide**. The following section summarizes the status and trends of some of the most important pollutants in Minnesota's atmosphere.

Smog-causing pollutants

Smog is a complex mixture of pollutants. Burning fossil fuels produces nitrogen oxides, sulfur dioxide, and volatile hydrocarbon compounds. When energized by sunlight, these chemicals react with other compounds in the atmosphere to form new, potentially harmful compounds (MPCA 1997a). Ozone is one of the most destructive of these new compounds and is an important component of smog. The same substance that absorbs harmful ultraviolet rays in our upper atmosphere is a corrosive pollutant that damages crops and injures the lungs of humans and other animals at ground level (MPCA 1997a). Nitrogen oxides also contribute to acid rain, forming corrosive nitric acid in reaction with water vapor (MEQB 1988).

Hydrocarbons are the combustible components of gasoline, oil, coal, wood, and natural gas. While complete combustion of hydrocarbons produces only carbon dioxide and water, combustion is seldom complete. The resultant mix of sooty chemicals contributes to urban smog, and some of these chemicals, such as benzene, have harmful effects on humans. Motorized vehicles produce 29 percent of the hydrocarbons released in the state and 87 percent of benzene emissions in the Twin Cities area (Sigford and Eleff 1992).

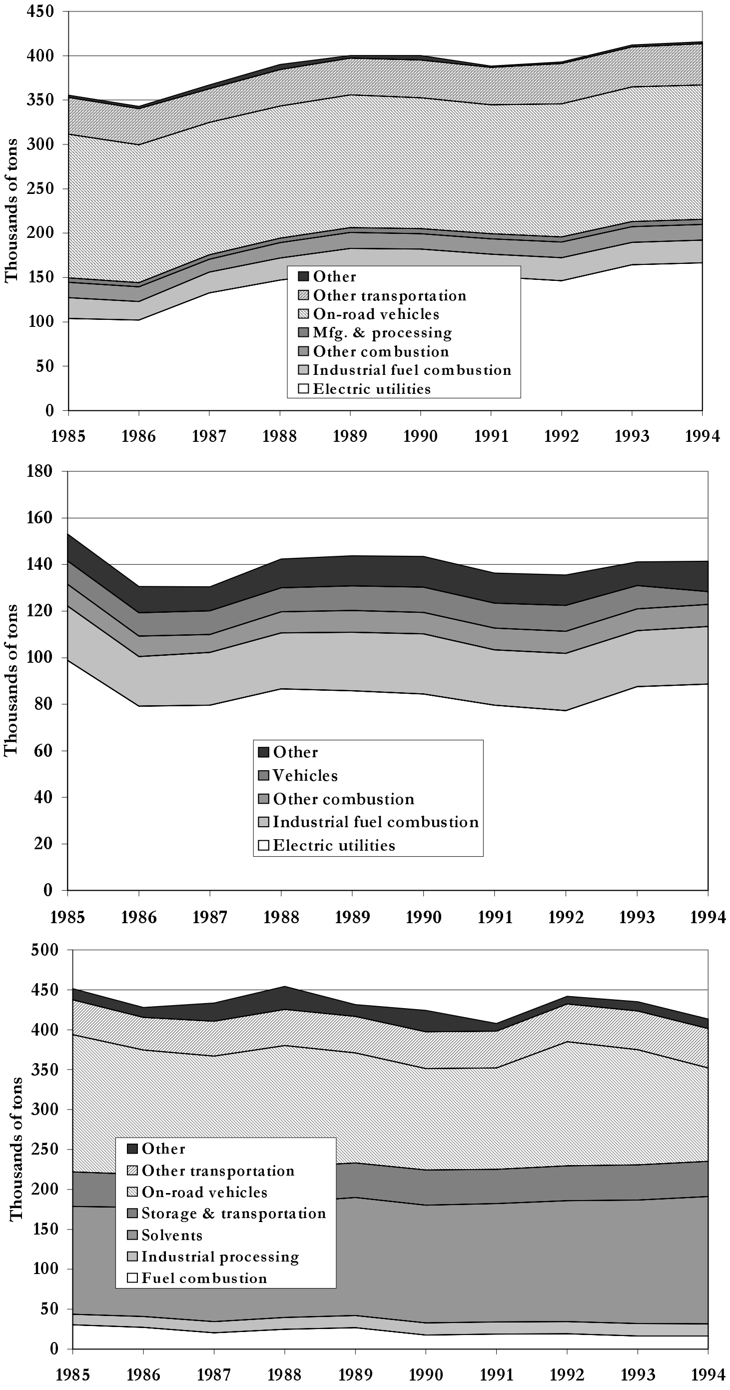
Sulfur dioxide originates when sulfur-containing fuels, such as coal and oil, are burned. Sulfur dioxide irritates lungs and eyes and contributes to smog. Asthma attacks, including tightening of the chest and difficulty breathing, can be triggered in sensitive people by low levels of sulfur dioxide. An estimated 50,000 to 150,000 asthma incidents are triggered each year in Minnesota by sulfur dioxide (MPCA 1997a). Sulfur dioxide also reacts with moisture to form sulfuric acid, an important contributor to **acid precipitation** (acid rain and acid snow). Acid precipitation can significantly degrade natural systems by altering water chemistry; it is corrosive to living tissues and hastens the breakdown of buildings, statues, and other cultural structures.

In Minnesota, **emissions of nitrogen oxides, sulfur dioxide, and volatile hydrocarbons** have remained fairly constant or have increased slightly since 1985 (Figure 9) despite population and economic growth. Combustion of fossil fuels accounts for most emissions of nitrous oxides and sulfur dioxide, and **solvent use** and **fuel combustion** account for most emissions of volatile hydrocarbons. As in the rest of the nation, control of point sources (industrial facilities) has slowed the increase in emissions of smog-causing pollutants in Minnesota. Factories and coal-fired power plants have switched to low-sulfur coal and installed stack scrubbers to remove sulfur dioxide from smokestack gases. However, mobile and area sources continue to be a problem. Future regulation may include better control of nitrous oxides produced by automobiles and tighter standards for emissions of these pollutants by area sources.

Minnesota's air quality remains very good by national standards. Minnesota is one of a very few states entirely in compliance with the current federal standard of 0.12 ppm for **ground-level ozone** (MEQB 1988; MPCA 1997a). Under a more

Figure 9

Emissions of NO_x, SO_2, and VOCs in Minnesota



stringent standard that more effectively reduces potential injury to humans and vegetation, the Twin Cities might not be in compliance for ground-level ozone (MPCA 1997a). Appropriate ozone-reduction measures would then have to be enacted.

Particulate matter

Particulate matter includes particles of dust, soot, smoke, or liquid droplets that are emitted by factories, power plants, cars, and construction activities, and that enter the atmosphere via fire, natural windblown dust, and condensation from other atmospheric materials (US EPA 1995). Particulates less than 10 microns in diameter are responsible for the majority of adverse health effects. These tiny particles are able to penetrate deep into lungs and cause irritation and tissue damage. For this reason, the smallest particulates are closely regulated by the U.S. Environmental Protection Agency (US EPA).

Particulate pollution from factories, power plants, and automobiles has been controlled through **monitoring programs** and **installation of pollution control equipment**. In the 1940s and 1950s, important sources of particulate matter included transportation (railroads and on-road vehicles), industrial processes, fuel combustion for heating, and wildfires. Today, fuel combustion and metal processing are the main sources of particulate pollution (Figure 10). Wind erosion can contribute significant amounts of dust and dirt to the atmosphere, but this effect is highly variable. During the drought of 1988, nationwide contributions of **wind-caused particulate matter** were estimated at 18 million tons, compared to 2 million tons during the flood year 1993 (US EPA 1995).

In Minnesota, only a small portion of St. Paul fails to meet federal ambient air standards for particulates (MPCA 1997a). Fine particles from chimneys and smokestacks are generally well controlled by equipment such as electrostatic particulate traps (MEQB 1988). Particulates from excavation sites and agricultural fields are harder to control, but conservation tillage practices and prompt revegetation on dig sites can help.

Current standards that regulate particles smaller than 10 microns in diameter may not be stringent enough to protect human health. Particles smaller than 2.5 microns appear to cause the greatest problems for health, and provisions now under consideration may focus more closely on this size class (MPCA 1997a).

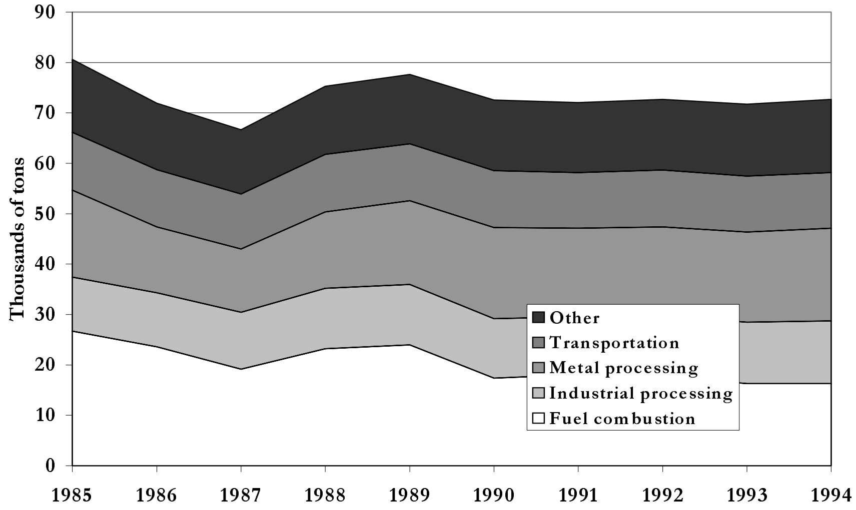
Urban toxic pollutants

Urban toxic pollutants include hundreds of different pollutants, ranging from dust to cancer-causing hydrocarbons (MPCA 1997a). Some of these compounds, such as benzene and formaldehyde, are known to cause cancer or birth defects in laboratory animals. However, at the low concentrations typical in urban air, the impact of most urban toxic pollutants on human health is not well documented (MPCA 1997a).

Carbon monoxide is one of the most common urban toxic air pollutants. It is a colorless, odorless gas that results from incomplete burning of wood or fossil fuels. Carbon monoxide can be poisonous because it replaces oxygen in our bloodstream, binds tightly to hemoglobin, the blood protein that transports oxygen, and prevents the blood from carrying enough oxygen to our cells. Exposure to high concentrations of carbon monoxide

Figure 10

Particulate Matter Emission in Minnesota

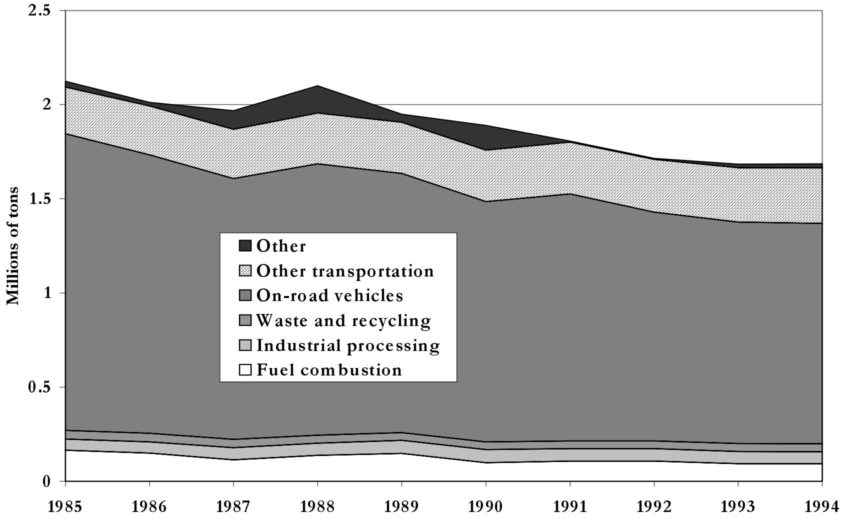


can be fatal; in smaller doses it causes headaches, muscle aches, and other symptoms of oxygen deprivation. Carbon monoxide from mobile outdoor sources, particularly automobiles, may accumulate in areas where traffic is heavy and the air is stagnant. Motorized vehicles produce 69 percent of the carbon monoxide in the Twin Cities area (Sigford and Eleff 1992).

Although **emissions of carbon monoxide** have decreased in Minnesota in recent decades (Figure 11) largely because of better controls on automobile emissions, excessive levels still occur, particularly in traffic-congested cities. In addition to carbon monoxide-reducing technologies required for automobiles by the federal government, Minnesota tests vehicle emissions in the metropolitan area. The program, initiated in 1991, requires vehicle owners to keep engines maintained for efficient combustion and minimum carbon monoxide production. Oxygenated gasoline is also sold in some areas, reducing carbon monoxide production, especially in cold weather (MPCA 1997a). These two programs reduce emissions by an estimated 180,000 tons of carbon monoxide each year (MPCA 1997a). Timed signal lights have also reduced carbon monoxide build-up at busy urban intersections (MEQB 1988).

Figure 11

Emission of Carbon Monoxide from Fuel Combustion in Minnesota



Indoor air pollution

Between 80 and 90 percent of the urban population's time is spent indoors (MEQB 1988). In recent years, as buildings have been better insulated for energy efficiency, concerns have arisen that certain chemicals may concentrate indoors to irritating or toxic levels. These include cigarette smoke, formaldehyde (used in the manufacture of foam insulation and synthetic carpet), and asbestos. The Minnesota Clean Indoor Air act recently banned smoking in all public buildings, and more and more workplaces are taking steps to remediate or eliminate other indoor air hazards.

Another concern for **indoor air quality** is radon, a radioactive gas that can seep into homes and concentrate to unhealthy levels. Long-term exposure to radon is associated with an increased likelihood of lung cancer. Radon is a naturally occurring by-product from the decay of uranium in rocks, with some rocks (e.g., granites) emitting more than others (MEQB 1988). No radon hot spots have been identified in Minnesota, but a survey by the Minnesota Department of Health found that up to 40 percent of Minnesota homes may have radon levels above US EPA guidelines (MEQB 1988). Increased venting of basements and other areas near ground level where radon may accumulate usually is effective in reducing radon levels.

Persistent toxic pollutants

Persistent toxic pollutants include industrial chemicals such as dioxins and polyaromatic hydrocarbons (PAHs) and heavy metals such as mercury and cadmium. All of these are poisonous substances that are not readily degraded and last a long time in the environment (MPCA 1997a). These substances can travel long distances by air, raining out into water and soil, and may accumulate in the tissues of plants and animals, causing various health problems.

Persistent toxic pollutants are of special concern because low levels in the environment quickly accumulate to high levels as they move up the food chain. A fish or animal may accumulate the dioxins and mercury it eats. If that fish or animal is eaten by another, the whole body burden of these substances passes to the consumer. Humans can be exposed to high levels of persistent toxic substances by eating game fish and turtles. At high levels, these substances pose health risks. Dioxins have been shown to cause cancer in laboratory animals. PAHs, a broad class of chemicals, also may cause cancer and can decrease fertility in lab animals. Mercury causes kidney damage and damage to or impairment of the brain and nerves. Lead, another persistent toxic substance, can cause acute poisoning and brain damage.

Once emitted into the air, dioxins, mercury, and some other persistent toxic pollutants are carried long distances by wind. Measurable amounts persist in the atmosphere but also easily accumulate in aquatic sediments and in the tissues of fish and fish-eating animals. The Minnesota Department of Health provides advisories on the consumption of many species of fish (MDH 1996).

Mercury enters the atmosphere when it volatilizes from spills, when coal is burned, and when mercury-containing consumer products, such as batteries, thermometers, and some paints, are incinerated. Once in the atmosphere, the mercury may be transported long distances before it is deposited onto forests, fields, wetlands, lakes, and rivers. Although Minnesota has strictly regulated in-state mercury emissions from incinerators and has eliminated many point-sources (Sigford and Eleff 1992), unsafe levels of mercury still exist even in remote parts of the state (Swain et al. 1992). Regular consumption of fish with even small levels of mercury may cause health problems in humans and other animals. Because mercury can cause severe birth defects, pregnant women should be especially careful to limit consumption.

Globally, mercury deposition has increased steadily since the mid-1800s. In Minnesota, however, **mercury deposition from atmospheric sources** may have decreased since the 1970s. Regional and global sources of atmospheric mercury appear to be more important than local sources as contributors to aquatic systems (Swain et al. 1992); although current rates of deposition in Minnesota are lower than in 1970, lakes still show elevated mercury levels.

Lead, a heavy metal once added to gasoline and used as a pigment in paints, causes serious health problems. Acute (short-term) exposure to high levels of lead results in a syndrome of physical impairments called lead poisoning. Chronic (long-term) exposure causes neurological damage that interferes with memory and learning. Children and developing fetuses are especially vulnerable; exposure to high levels of lead while brain tissue is forming can cause life-long impairment.

Lead pollution has been sharply reduced in recent years through bans on lead in gasoline and house paint. Airborne lead has been dramatically reduced since the mid-1970s by federal policy requiring new cars to burn lead-free gasoline. The reduction in emissions from 219,000 tons in 1970 to 5,000 tons in 1994 was due primarily to the shift to unleaded gasoline. Minnesota's stringent standards for **lead emission** from industrial sites also have helped cut airborne lead levels (MEQB 1988). However, emissions of lead are on the rise again due to increased industrial activity and increased emission of lead by electrical utilities (US EPA 1995).

Acid precipitation (acid rain, acid snow)

Nitrogen oxides and sulfur dioxide, formed when fossil fuels are burned, react in the atmosphere to form nitric and sulfuric acids. These acids travel widely through the atmosphere and eventually are incorporated into rain or snow. They fall to earth as acid precipitation, which corrodes buildings and seriously damages forests and aquatic ecosystems (Taylor et al. 1994). Acid rain injures tree leaves and needles, interferes with soil nutrient cycles, and kills fish and amphibian eggs.

Acid rain is an issue that crosses regional boundaries. Because 90 percent of the acid deposited in Minnesota is generated outside the state, cooperation between various states and Canada (MEQB 1988) is necessary for effective reductions in **acid deposition**.

While acid precipitation is a serious problem in New England and central Europe, recent monitoring data suggest that it is not a significant problem in Minnesota. Many of Minnesota's lakes are buffered by alkaline, limestone-rich bedrock, and the geologically more vulnerable northern lakes receive only moderate amounts of acid fallout due to prevailing wind patterns. Nevertheless, 8 million acres of Minnesota lakes and forests may be susceptible to acid damage, including 2,000 lakes in the state's north and northeast regions (MEQB 1988).

Existing Policies and Programs

The federal Clean Air Act assigns the state significant responsibility for maintaining air quality. In Minnesota the Minnesota Pollution Control Agency (MPCA) is the lead agency in maintaining Minnesota's air quality. In consultation with the US EPA, MPCA sets **air quality standards**, analyzes pollution levels, and monitors **compliance with air emission standards**. Minnesota is one of only eight states that have acted on the authority given in the Clean Air Act to develop air quality standards for some pollutants that are more stringent than the federal NAAQS (Sigford and Eleff 1992).

There are two levels of air quality standards: primary and secondary. These standards define the allowable hourly exposure to specific pollutants. Primary standards protect human health. If exposure to a pollutant is kept below the primary standard, even sensitive people should experience no ill effects (MEQB 1988). Secondary standards are intended to limit crop damage, injury to livestock, damage to property, annoyance, and transportation hazards (MEQB 1988). Although both primary and secondary standards are established by the federal government, states retain the right to set standards that are more stringent. For example, Minnesota enforces a standard for short duration (1-hour) exposure to sulfur dioxide that does not exist at the federal level (MEQB 1988).

States may also modify standards to fit local needs. For instance, to protect white pine and other acid-sensitive species in Minnesota's northern forests, the state has two standards for sulfur dioxide. The more stringent standard applies to areas north of St. Cloud (MEQB 1988).

Of about 2,200 air emission facilities in the state, ranging from small school boilers and rural grain elevators to petroleum refineries and coal-burning power plants, approximately 1,500 sites (nearly 70 percent) are required to obtain MPCA air emission permits (MPCA 1997a). The MPCA recognizes two classes of permitted facilities: those emitting between 25 and 100 tons of pollutants per year, and those emitting more than 100 tons per year. Facilities emitting less than 25 tons per year are generally exempt from permits, although operations likely to cause a local nuisance may be reviewed on a case-by-case basis (MEQB 1988). Large facilities are issued one permit for total facility emissions, streamlining an earlier process whereby permits were granted for individual pieces of equipment (MEQB 1988). With **total facility permits** (TFPs) in place, the MPCA can more effectively monitor pollution from each facility and make recommendations for keeping emissions within standards.

Pollution reduction is the main goal of most air-quality control policies. Regulators seek to balance the need to protect the health of humans and the environment by reducing pollution levels with society's demand for the goods and services that produce air pollution. Broad measures to protect our air began in 1967 with the passage of the federal Air Quality Act. This act provided the authority to each state to set air pollution standards and plan control strategies to meet them. The act was modified into the Clean Air Act of 1970, laying the foundation for most of the regulatory efforts since that time (Quarles and Lewis 1990). Additional revisions occurred in 1974, 1977, and 1990. The 1990 amendments set new deadlines for meeting target emissions, added new control requirements, and required more stringent regulations on automobile emissions.

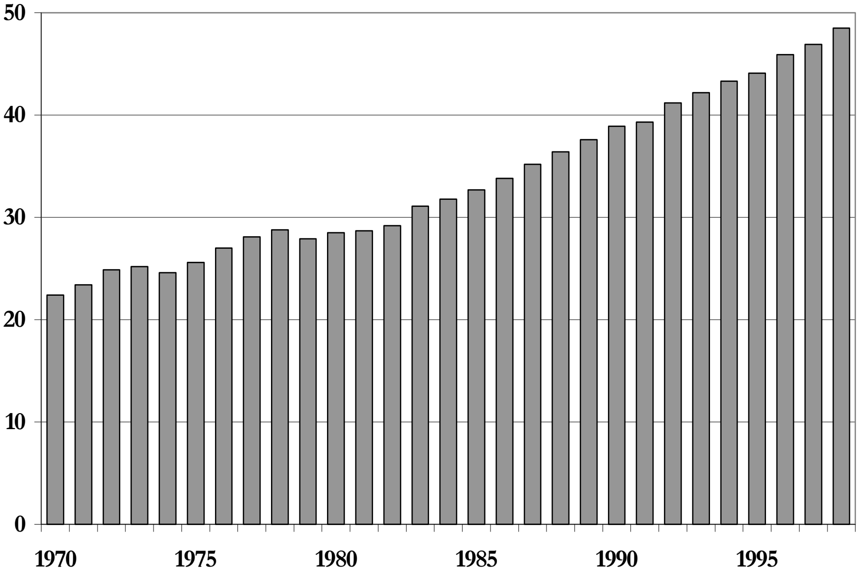
As part of the 1970 Clean Air Act, nationwide standards were established for a set of criteria pollutants. These pollutants include common substances that are known to impair human health: particulate matter, sulfur dioxide, carbon monoxide, nitrogen oxides, ozone, and lead. The National Ambient Air Quality Standards (NAAQS) are based on scientific determinations of the thresholds for air pollution above which adverse effects are experienced by humans or the environment (Quarles and Lewis 1990). The standards aim to prevent deterioration of air quality and to encourage pollution reduction even in areas with good air quality. They have been criticized both for being too stringent because they require that even the most vulnerable citizens suffer no effects from each regulated pollutant, and for being too weak because they do not consider the effect of multiple pollutants on a person's health (Quarles and Lewis 1990). Establishing acceptable limits on pollutants, revising those limits when appropriate, and encouraging conservation and clean technology are some of the goals of air-quality control regulators.

Monitoring is an important component of the MPCA's activities. MPCA maintains a network of air-quality monitoring stations across the state. Most of these stations are located near point sources of pollution, such as factories and busy intersections. The MPCA also requires some factories to maintain their own air-quality monitoring stations (MPCA 1988). In recent years, MPCA's monitoring programs have emphasized pollutants associated with acid deposition, mercury deposition, and the criteria pollutants. As permitted under the 1970 Clean Air Act, Minnesota also requires Continuous Emission Monitors for several types of facilities, including electrical utilities, paper mills, solid and hazardous waste incinerators, petroleum refineries, and wastewater treatment plants (Sigford and Eleff 1992).

In addition, Minnesota has implemented an **automobile emissions inspection program** that targets carbon monoxide, carbon dioxide, and hydrocarbons (including the volatile organic compounds (VOCs) that are precursors to ozone smog development). As the **number of vehicle miles driven in Minnesota** increases (Figure 12), automobile emissions will be an ever greater threat to air quality in Minnesota. Finally, the Minnesota Emergency Planning and Community Right-to-Know Act of 1989 requires that companies report on the storage and release of hazardous chemicals and make that information available to local communities.

Figure 12

Vehicle Miles Traveled in Minnesota



EXAMPLE INDICATORS

Table 2 lists potentially useful indicators of air quality. The indicators are organized within the EII framework, which helps illustrate relationships between human activities, environmental condition, the flow of benefits from the environment, and strategies for sustaining a healthy environment. These indicators are examples that illustrate how indicators may help assess the condition of the atmosphere.

Table 2
EXAMPLE INDICATORS

HUMAN ACTIVITIES	ENVIRONMENTAL CONDITION	SOCIETAL STRATEGIES
Large scale alteration of natural ecosystems **Construction and expansion of urban environments** **Emissions** greenhouse gases ozone depleting chemicals sulfur dioxide, ozone, volatile organic compounds, lead, and carbon monoxide nitrogen oxides, sulfur dioxide, and volatile hydrocarbons **Vehicle miles driven in Minnesota** **Production and consumption of CFCs** **Solvent use** **Fuel combustion**	**Nitrogen availability due to deposition** **Temperatures in urban centers** **Concentrations of greenhouse gases in the atmosphere** **Global average temperature** **Average rainfall** **Average annual temperature in Minnesota** **Stream flows** **Lake temperatures** **Atmospheric ozone concentration** **Rate of damage to genetic material** **Acid predipitation** **Ground level ozone** **Wind-caused particulate matter** **Indoor air quality** **Mercury deposition from atmospheric sources**	**Pollution reduction regulations** **Reduction of fossil fuel use** **Reforestation** **Urban tree planting** **Monitoring programs** **Installation of pollution control equipment** **Air quality standards and enforcement** **Total Facility Permitting** **Automobile emissions inspection programs**

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