United States General Accounting Office

GAO

Report to Congressional Requesters

April 2003

CLIMATE CHANGE

Information on Three Air Pollutants' Climate Effects and Emissions Trends

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GAO-03-25

Highlights

Highlights of GAO-03-25, a report to Congressional Requesters, House of Representatives

Why GAO Did This Study

Solar radiation is absorbed by the earth and is subsequently reemitted. The buildup of carbon dioxide and certain other gases in the earth's atmosphere traps some of that radiation. This is known as the greenhouse effect and is believed to contribute to a warming of the earth's climate. Concerns are growing that, in addition to carbon dioxide and other conventional greenhouse gases, certain air pollutants may affect the climate.

GAO was asked to examine (1) the extent of agreement among scientists regarding the effect on the climate of three air pollutants—black carbon (soot), ground-level ozone, and sulfate aerosols—and (2) seven countries' efforts to control these pollutants, trends in these substances in these countries over the past 2 decades, and estimates for the next decade. GAO was also asked to summarize the relationship between economic growth and environmental pollution.

The seven countries include four that are economically developed—Germany, Japan, the United Kingdom, and the United States—and three that are developing—China, India, and Mexico. These countries were chosen because they have large economies with a high potential to emit these pollutants.

The two federal agencies asked to comment generally agreed with the information presented in this report.

www.gao.gov/cgi-bin/getrpt?GAO-03-25.

To view the full report, including the scope and methodology, click on the link above. For more information, contact John B. Stephenson at (202) 512-3841.

April 2003

CLIMATE CHANGE

Information on Three Air Pollutants' Climate Effects and Emissions Trends

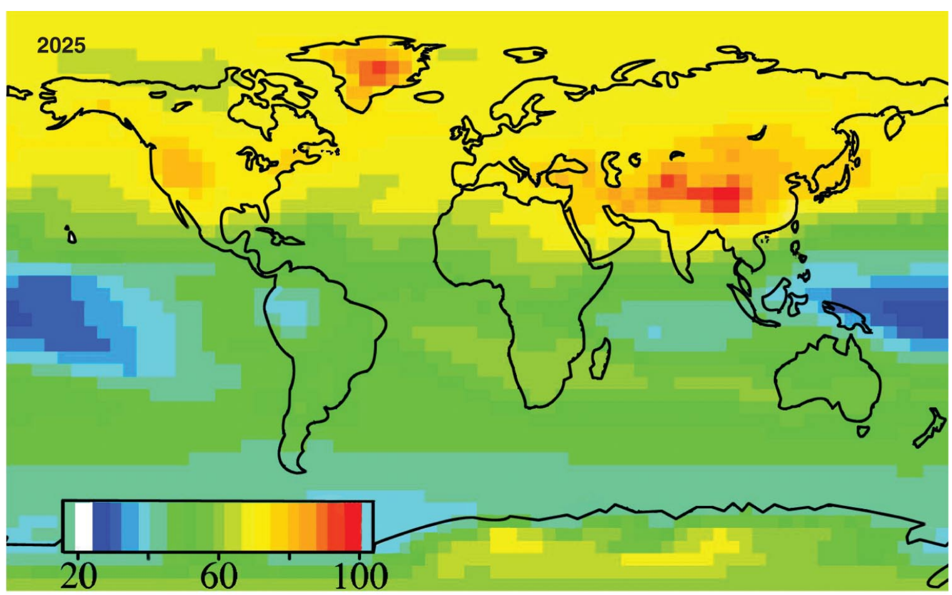
What GAO Found

Scientists generally agree that sulfate aerosols have a cooling effect on climate, while ozone in the lower atmosphere has a warming effect. Black carbon tends to warm the atmosphere but cool the earth's surface. Sulfate aerosols also affect how much and where it rains. Considerable uncertainty remains about the size of these effects.

All seven countries are taking steps to reduce the amounts of the three pollutants. The four economically developed countries have well-established efforts underway. In these countries, the amounts of the three substances generally declined over the last 2 decades and are expected to decline over the next decade. In contrast, the three developing countries' efforts are less well established. In these countries, the amounts of the three substances generally increased during the years for which information is available. GAO found few projections for these three countries.

An extensive body of research has examined the possible connection between economic development and environmental pollution, but the results of this research are inconclusive. Researchers also caution that economic growth by itself may help support environmental improvements but is not, by itself, sufficient to ensure them.

Projected Average Global Ozone Concentrations, Parts per Billion, 2025



Blue areas indicate low ozone concentrations

Yellow and red areas indicate high ozone concentrations

Source: L.J. Mickley, Harvard University.

Contents

Abbreviations

CLRTAP	Convention on Long-Range Transboundary Air Pollution
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change

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United States General Accounting Office
Washington, D.C. 20548

April 28, 2003

The Honorable W. J. (Billy) Tauzin
Chairman
Committee on Energy and Commerce
House of Representatives

The Honorable Joe Barton
Chairman, Subcommittee on Energy and Air Quality
Committee on Energy and Commerce
House of Representatives

The Honorable James C. Greenwood
Chairman, Subcommittee on Oversight and Investigations
Committee on Energy and Commerce
House of Representatives

Carbon dioxide and certain other gases in the earth's atmosphere trap the sun's heat and prevent it from escaping back into space. This phenomenon, known as the greenhouse effect, tends to warm the earth's surface; the gases that cause it are called greenhouse gases. Most scientists agree that a change in the earth's climate could have wide-ranging effects on economies, ecosystems, and human habitation. Climate change could make some locations unsuitable for growing traditional crops, which could lead to economic disruptions, especially in agricultural economies. However, warming is not the only issue of concern with respect to greenhouse gas emissions. A buildup of such gases could also alter precipitation patterns, causing some areas to receive more rain and others to become drier. Extreme events, such as drought or floods, could become more frequent. In addition, if climate change causes sea levels to rise substantially, low-lying areas might become uninhabitable, forcing the dislocation of entire populations. Evidence suggests that climate change is the result of both human actions (such as fossil fuel burning) and natural phenomena (such as solar variability). However, according to an international panel of experts, most of the warming observed over the past 50 years is attributable to human activities.

In recent decades, concentrations of greenhouse gases have built up in the atmosphere. Concerned about these increased concentrations, the United States and many other nations entered into a treaty to stabilize atmospheric concentrations of greenhouse gases at levels that would prevent dangerous human interference with the climate system.

The United States ratified this treaty, the United Nations Framework Convention on Climate Change (UNFCCC), in 1992. Of the gases covered by the treaty, the most important in terms of contribution to warming, are, in declining order of emissions levels, carbon dioxide, methane, nitrous oxide, and three types of synthetic (manufactured) gases.

In addition, scientists have recently intensified their efforts to study the climate effects of substances not included in the Framework Convention. According to a 2001 comprehensive review[1] of scientific research on climate change, additional substances—generally regarded as air pollutants because they can damage human health and the environment—can also affect the earth's climate. Among the substances are the three treated in this report, listed below. Of these three, sulfate aerosols exert the greatest influence on climate.

- **Sulfate aerosols** are produced when sulfur dioxide gas is transformed through oxidation[2] in the atmosphere into aerosol particles. (An aerosol is a solid and/or liquid particle suspended in the air.) Sulfur dioxide is produced mainly by burning coal and petroleum products that contain sulfur.

- **Black carbon** is a type of aerosol produced by the incomplete burning of substances containing carbon. Significant sources include uncontrolled or poorly controlled combustion of coal, diesel fuel, and biomass for heating and cooking, and by the burning of fields and forests. Black carbon emissions from these sources are accompanied by varying amounts of particulate organic materials.

[1] Intergovernmental Panel on Climate Change (IPCC), 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, New York.

[2] Oxidation is a type of chemical reaction involving oxygen.

- **Tropospheric ozone**[3] is formed when nitrogen oxides react with certain other chemicals in the presence of sunlight. Nitrogen oxides are produced primarily by cars and other vehicles and by power plants that burn fuel to generate electricity. On a global scale, methane and carbon monoxide are also significant precursors to ozone.

You asked us to (1) assess the extent to which the scientific community agrees on the climate effects of sulfate aerosols, black carbon, and ozone, as reflected in the 2001 review, and identify important developments since that review, and (2) identify trends in emissions and concentrations of these three substances over the past 2 decades in the United States and six other specified countries, identify projected estimates in emissions and concentrations of these pollutants in all seven countries over the next decade, and determine each country's actions to reduce these three pollutants. In addition, you asked us to review the existing literature on the effect of economic development on a country's pollution levels to determine whether, as some researchers have suggested, there is a systematic connection between growth in income and emissions. As agreed with your offices, we examined the United States and three other economically developed countries (Germany, Japan, and the United Kingdom) and three economically developing countries (China, India, and Mexico). These countries were chosen because they have large economies with a high potential to produce the substances we examined.

To obtain information on recent research relating to the climate change characteristics of the three substances, we relied primarily on the *Third Assessment Report*, the most comprehensive source on climate science. We also contacted scientists in four federal agencies, who were recommended by staff at the U.S. Climate Change Science Program, which coordinates and supports government research on climate change. To learn about work subsequent to the 2001 review, we reviewed published work recommended by experts in the field. In obtaining data on emissions trends and projections, we found that data from government and academic

[3] Wherever it is found, ozone is chemically the same, a molecule comprised of three oxygen atoms. Its effects depend on its location. In the earth's upper atmosphere (called the stratosphere), ozone is beneficial because it prevents ultraviolet radiation—which is dangerous to human health—from reaching the earth's surface. However, at lower levels (called the troposphere), it is harmful to human health. Ozone in the stratosphere also has impacts on climate. It is formed by different means than ozone in the troposphere. We do not discuss stratospheric ozone at length in this report because it is produced mainly through natural (non-human-induced) processes. Unless otherwise stated, when we refer to ozone, we are referring to tropospheric ozone.

sources in the United States and the other six countries varied considerably in terms of quality and availability. In cases where no other estimates were available, we used results prepared by leading researchers in the field. With respect to the types of policy measures reviewed, we concentrated on regulatory measures and did not include research and development programs, programs of a voluntary nature, emissions monitoring requirements, or programs to disseminate information or educate the public. We further focused on existing programs or programs already authorized and excluded proposed programs. We also excluded the policies and measures taking place at the sub-national level (state or province level, for example), which are separate from, though sometimes complementary to, national measures. For more information on how we gathered information for this study, see appendix I.

Results in Brief

The scientific community substantially agrees that black carbon aerosols warm the atmosphere and cool the earth's surface, while ozone contributes to warming the earth, and sulfate aerosols contribute to cooling it, according to the 2001 review, other scientific literature, and discussions with atmospheric scientists. However, scientists are uncertain about the extent of these effects. They believe that the level of uncertainty associated with these pollutants is moderate for ozone and high for black carbon and sulfate aerosols. While carbon dioxide and the other traditional greenhouse gases generally contribute to temperature and other effects at a global level, the three substances considered here operate on a different scale, both in terms of time and geography. These three substances can have effects over smaller distances and shorter time frames. In other words, their impacts tend to be more important locally and regionally, while having a smaller influence globally. Because of relatively rapid removal from the atmosphere, their impact may be felt in the short-term, as opposed to over decades or centuries hence. However, the effects of these substances are not limited to warming; these substances may also cause local cooling or may change local precipitation patterns. Since the 2001 review, other research has added to scientists' understanding of the effects of black carbon. For example, air and clouds over the Indian Ocean (which are polluted with black carbon, sulfates, and other aerosols) were found to absorb the sun's energy to a far greater extent than expected. These results suggest that black carbon, the only one of these substances that absorbs rather than reflects light, may play a more important role in warming the atmosphere than was estimated in the 2001 review.

All seven countries are taking steps to reduce the amounts of the three pollutants. In the United States and the other three economically developed countries we studied, these efforts have been underway for decades. For example, these countries limit emissions from power plants that burn coal and other fossil fuels. They also regulate emissions from automobiles and trucks. In these four countries, the amounts of the three substances generally declined over the last 2 decades. For example, sulfur dioxide emissions declined in all four countries and black carbon emissions declined in three countries. Although sulfur dioxide emissions are expected to decline in all of these countries, we found no emissions projections for black carbon for three of them. Although developed countries have made progress in reducing domestic ozone concentrations, global ozone concentrations are likely to increase, owing to rising emissions of ozone precursors in other countries. In contrast, in China and the other two developing countries, emission control efforts are more recent, typically going back only a decade or so. As in the developed countries, these countries also target power plants and motor vehicles to control emissions. In the developing countries, the levels of the three substances varied. Sulfur dioxide emissions decreased in two countries, but black carbon emissions increased in two countries. We found limited information on ozone concentrations in developing countries. Most available data pertain to only a few major cities and is not nationally representative. Similarly, we were unable to find projections for sulfur dioxide and black carbon emissions for these countries. The quality of data, especially for developing countries, is uneven.

The results of empirical and theoretical research on the effect of economic growth on environmental pollution are inconclusive. This research has examined the hypothesis that pollution initially worsens as an economy grows, but then improves as economic growth continues and income rises. Empirical studies, which analyzed historical data to find such a relationship across pollutants, have had mixed results. Similarly, theoretical studies, which sought to identify how economic growth may affect environmental pollution, have produced various possible explanations but reached no consensus. Researchers agree that improved data and more detailed studies will be needed to identify how economic growth affects environmental pollution. Also, researchers caution that economic growth does not automatically lead to reduced pollution. They explain that, while economic growth may be necessary to provide the resources needed to protect the environment, it is not, by itself, sufficient to reverse environmental degradation and that appropriate environmental policies must follow.

Background

Although the sun heats the earth's surface, a large fraction of the sun's energy is reflected back into space by clouds, ground surfaces, ice, and water. However, certain gases in the earth's atmosphere, such as carbon dioxide and methane, trap some of the sun's heat and prevent it from returning to space. The trapped energy warms the earth's climate, much like glass in a greenhouse. Hence the gases that cause this effect are often referred to as greenhouse gases.

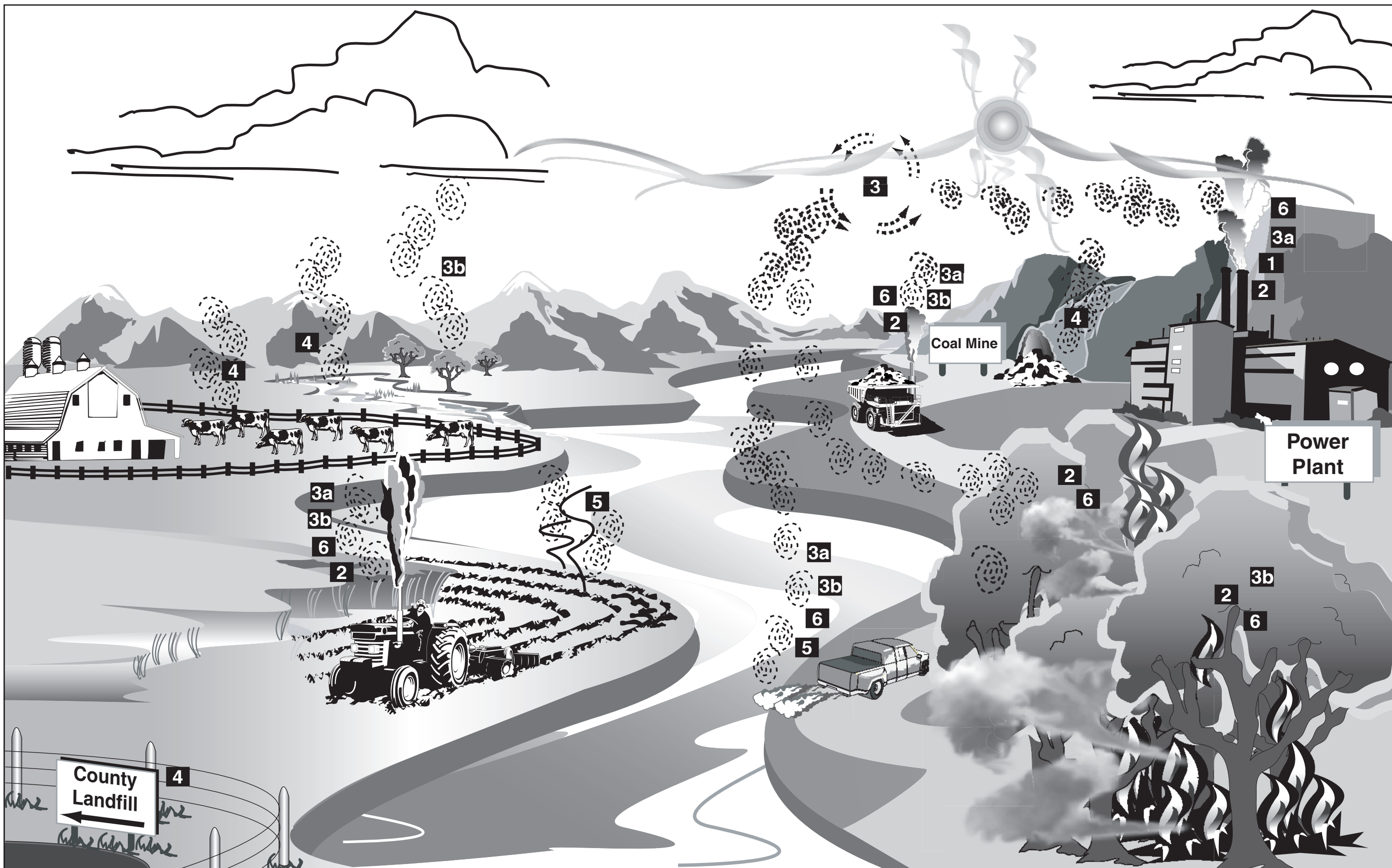
In response to potential environmental problems linked to the emissions of various heat-trapping gases, the United States and many other nations in 1992 signed a treaty aimed at limiting climate change induced by human activity. This treaty, called the United Nations Framework Convention on Climate Change, seeks to stabilize atmospheric concentrations of greenhouse gases at levels that would prevent dangerous human interference with the climate system. Under the 1992 convention, the United States and other parties generally agreed to implement programs aimed at reducing their emissions of greenhouse gases not covered by another treaty, the Montreal Protocol.[4] The most important of these warming gases, in declining order, are carbon dioxide, methane, nitrous oxide, and three types of synthetic (manufactured) gases—sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons.

[4] The Montreal Protocol, ratified by the United States in 1988, aims to reduce the use of substances that deplete stratospheric ozone. Among these substances are chlorofluorocarbons, which are also potent greenhouse gases.

In recent years, scientists have focused increased attention on the climatic role of certain substances that are regarded as air pollutants (because of their harmful effects on human health and the environment) but are not covered by the Framework Convention or Montreal Protocol. These substances are aerosols (including sulfate aerosols and black carbon) and tropospheric ozone. Scientists have long recognized that these pollutants can affect climate, but these pollutants were not included in the Framework Convention. Sulfate and black carbon aerosols differ from traditional greenhouse gases, such as carbon dioxide and methane, in two key ways. First, unlike the traditional greenhouse gases, which are evenly distributed throughout the atmosphere and have global impacts, the effects of sulfate aerosols and black carbon are greatest near their sources, although they can have global impacts. Second, whereas traditional greenhouse gases can remain in the atmosphere for tens to hundreds, or even thousands,[5] of years, sulfate aerosols, black carbon, and ozone remain in the atmosphere for much shorter time periods. Figure 1 shows the sources and estimated mean atmospheric lifetimes of various substances having an impact on climate.

[5] Sulfur hexafluoride and perfluorocarbons, which are man-made greenhouse gases, have atmospheric lifetimes of several thousand years. They are not depicted in figure 1.

Figure 1: Sources and Estimated Mean Atmospheric Lifetimes of Selected Substances Affecting Climate



	Substance	Major sources	*Mean* atmospheric lifetime
1	Sulfate aerosols	Combustion of coal and oil (power plants)	Days to weeks
2	Black carbon	Incomplete combustion of fuels (diesel vehicles, forest fires, certain power plants, cook stoves)	Days to weeks
3	Tropospheric ozone	Produced in the atmosphere by reactions, in the presence of sunlight involving nitrogen oxides and volatile organic compounds, including methane and carbon monoxide	Days to weeks
3a	Nitrogen oxides	By-product of combustion (vehicles, power plants)	Days to weeks
3b	Volatile organic compounds	Vehicles, industrial processes, trees	Days to weeks
4	Methane[a]	Wetlands, cattle and other ruminant animals, fugitive emissions from coal mining, landfills	12 years
5	Nitrous oxide	Agricultural soil management (application of fertilizers), vehicles	114 years
6	Carbon dioxide[b]	Combustion of carbon-containing substances, such as combustion of coal, oil, or natural gas in power plants or gasoline in vehicles; also from land-use changes	50 to 200 years

Source: Illustration prepared by GAO with portions using Art Explosion. For sources of information on lifetimes and sources, see next page.

[a]Wetlands are a natural, as opposed to man-made, source of methane. We list them here because wetlands are the largest single source of global methane emissions.

[b]The lifetime of carbon dioxide depends on rates of absorption by oceans and vegetation.

Notes: For each substance, we depict only the most important sources. Additional sources of emissions exist for most of the substances listed above.

This graphic was prepared by GAO with lifetime data reported in IPCC's *Third Assessment Report,* 2001. Source data reported by EPA, *National Air Quality and Trends Report*, 1999; EPA, *Inventory of U.S. Greenhouse Gas Emissions 1990-2000*; and Elaine Matthews, "Global Methane Emissions: Historical Trends, Controlling Factors, and Future Prospects," in *Air Pollution as a Climate Forcing: Workshop Proceedings*, May 2002.

- **Sulfate aerosols** are created when sulfur dioxide emitted from, for example, coal- and oil-fired power plants, is oxidized in the atmosphere. Atmospheric sulfate aerosols have been associated with significant effects on public health and visibility impairment, and when they are deposited on earth, they contribute to the acidification of lakes, streams, and forests. Sulfate aerosol particles also have major effects on clouds, where they provide additional nuclei around which cloud droplets form. This can increase the cooling effect of clouds and may also increase the life spans of clouds. Both developed and developing countries burn coal to generate electricity, leading to emissions of sulfur dioxide.

- **Black carbon**, a type of aerosol, is a form of particulate matter and results from the incomplete combustion of coal, diesel fuel, and biofuels (such as alcohol or gasohol), and from open biomass burning, (i.e., the burning of forests and agricultural residues). Because it is dark in color, black carbon aerosol absorbs the sun's energy, creating warming in the atmosphere and cooling at the earth's surface, thus modifying climate (in contrast to the warming caused by traditional greenhouse gases, which prevent the earth's heat from escaping into space). Black carbon is generally released with other pollutants in different proportions.

- **Tropospheric ozone** is not emitted directly but is formed when emissions of other pollutants, called precursors, react in the presence of sunlight. Ozone precursors include nitrogen oxides (mainly nitric oxide and nitrogen dioxide) and several carbon-containing substances, namely carbon monoxide, methane, and non-methane volatile organic compounds. Nitrogen oxides are produced primarily by motor vehicles, other combustion engines, and electric power plants. Natural sources of nitrogen oxides are lightning and biological processes in soils. Carbon monoxide is formed when the carbon in fuels is not burned completely. It is a product of motor vehicle exhaust and industrial processes. Natural sources of carbon monoxide include wildfires. Methane is emitted by human activities, such as coal mining, natural gas and oil production, livestock production, rice cultivation, and waste disposal. It also comes from natural sources, including wetlands, and some animals, such as termites. Volatile organic compounds are produced by motor vehicles, industrial processes using solvents, and in some cases, by vegetation, including trees.[6]

[6] Isoprene and monoterpenes are examples of volatile organic compounds produced by vegetation.

In reviewing the scientific information on these three substances, we concentrated on the material covered in the most recent systematic published review, the IPCC's *Third Assessment Report*, which represents the consensus of many climate scientists.[7] We also included some more recently published material, notably the large-scale, multi-participant study of aerosols over the Indian Ocean, known as the INDOEX study, which was conducted in 1999. We included these results because they come from a large, well-recognized, international program whose objectives overlap substantially with many of the subject areas of this report.

The seven countries we reviewed differ greatly in terms of their population, total area, and per capita income. For example, population ranged from around 60 million in the United Kingdom[8] to nearly 1.3 billion in China; total area varied from just under 245,000 square kilometers for the United Kingdom to 9.6 million square kilometers for the United States; per capita income ranged from $2,200 in India to $36,300 in the United States. See table 1.

[7] IPCC's *Third Assessment Report*, 2001.

[8] The United Kingdom includes Great Britain (England, Scotland, and Wales) and Northern Ireland.

Table 1: Comparative Statistics of the Seven Countries Reviewed

Country	Estimated population (2002) (in millions)	Total area (square kilometers)	Per capita income, 2001
Economically developed countries			
United States	281.0	9,629,091	$36,300
United Kingdom	60.0	244,820	24,700
Germany	83.3	357,021	26,200
Japan	127.0	377,835	27,200
Economically developing countries			
China	1,284.3	9,596,960	4,301
India	1,045.8	3,287,590	2,200
Mexico	103.4	1,972,550	9,000

Source: GAO (table), Central Intelligence Agency's *The World Fact Book*, 2002 (data).

Notes: Some figures have been rounded.

Estimated gross domestic product per capita is based on purchasing power parity rates. Purchasing power parity asserts that a unit of currency, such as a dollar, should be able to buy the same bundle of goods in all countries.

In the 1960s, scientists determined that emissions of sulfur dioxide from European power plants were causing the acidification of Scandinavian lakes. Recognizing that air pollution does not respect national boundaries, 34 countries, including Germany, the United Kingdom, and the United States, signed the Convention on Long-Range Transboundary Air Pollution (CLRTAP) in 1979. Under a subsequent protocol to this convention, the signatories agreed to reduce their emissions of sulfur dioxide. Later, they extended the convention to further reduce sulfur dioxide and to reduce ozone precursors and various other pollutants.[9] There are now 49 parties to the convention.

In addition to commitments under this 1979 convention, several European countries, including Germany and the United Kingdom, are bound by European Union (EU) requirements to reduce emissions. For example, a 1996 framework directive set broad goals for the consistent management of several air pollutants, including sulfur dioxide, nitrogen oxides, and ozone, in member nations. In 1999, a supplemental directive established a legally binding limit on concentrations of sulfur dioxide and nitrogen oxides,

[9] The United States is party to some, but not all, of the CLRTAP protocols. Certain of the protocols extending the convention are not yet in force.

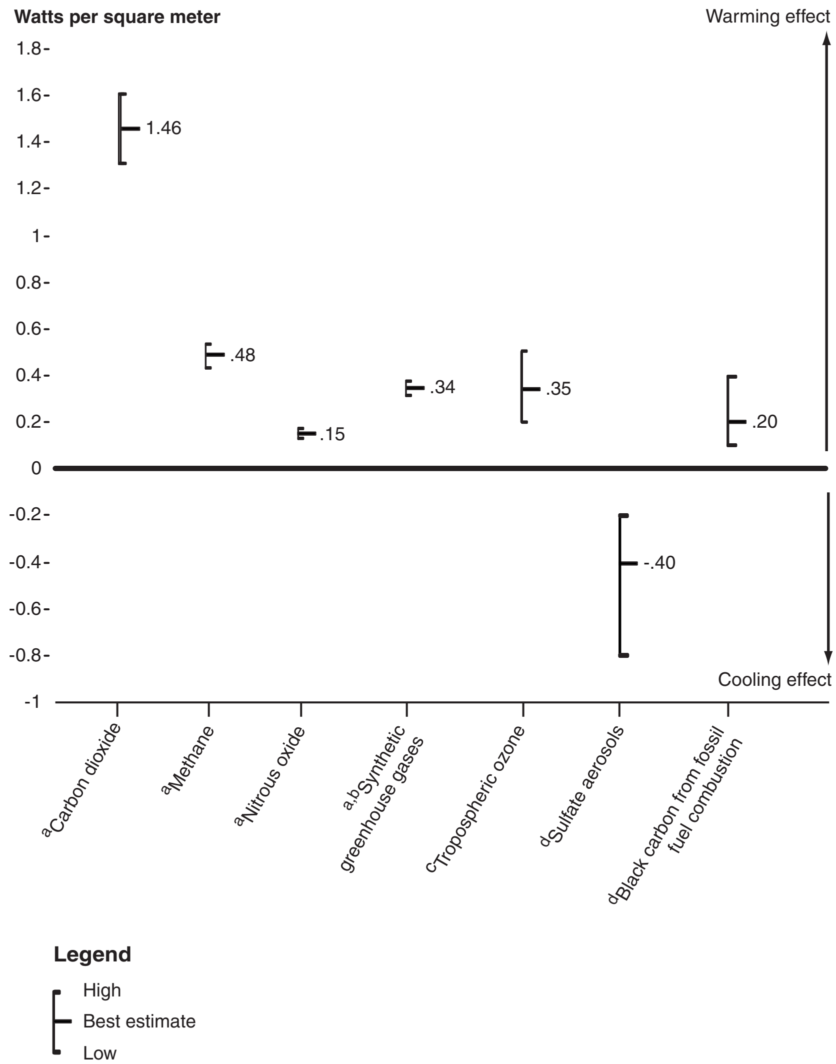
among other substances, to be achieved by all member countries by 2005. Another 1999 directive required EU countries to reduce the sulfur content of liquid fuel. (More information on the various directives can be found in apps. II, III, and IV.) Each EU member nation is required to transform the EU requirements into national legislation for domestic implementation. In general, the EU emission reduction targets are more stringent than the CLRTAP targets.

Scientists Agree on the Overall Direction of the Three Pollutants' Climate Impacts, but the Estimates of Impacts Contain Significant Uncertainties

According to the most recent comprehensive review of scientific research on climate change, published in 2001, scientists generally agree that sulfate aerosols tend to cool the earth, while black carbon aerosols and ozone tend to warm it. However, the extent of these effects is uncertain. Research published since 2001 has not changed these overall conclusions, but it does suggest that the scientific community's understanding of these effects is incomplete and needs further exploration.

The extent of the heating and cooling effects of various substances, as compared to pre-industrial conditions, is typically expressed in watts per square meter, which is a measure of energy per unit area. Changes in the balance between incoming and outgoing solar energy in turn heat or cool the earth. Specifically, the earth receives 342 watts per square meter of incoming solar radiation annually at the top of the atmosphere and reflects about 30 percent back into space, resulting in a net input of 240 watts per square meter. If the climate were in balance, the same amount of energy that the earth received would be emitted back into space as infrared radiation. However, warming gases trap some of this outgoing radiation, thereby changing the balance between incoming and outgoing radiation. Water vapor is the most significant greenhouse gas; carbon dioxide is the second most significant. Additional carbon dioxide added to the atmosphere by human beings since the industrial era has contributed another 1.46 watts per square meter averaged over the earth's surface annually, thereby further warming the climate. Figure 2 shows how the average effects of the three pollutants we reviewed compare with the climate effects of carbon dioxide and other conventional greenhouse gases.

Figure 2: Direct Effects of Several Substances on Climate Change as Reported in the IPCC's *Third Assessment Report*, 2001



Source: Intergovernmental Panel on Climate Change, *Third Assessment Report*, 2001.

[a]Estimated uncertainties for these substances are plus or minus 10 percent.

[b]Synthetic gases include hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

[c]Estimated uncertainty for ozone is plus or minus 43 percent.

[d]Please see notes below for a discussion of the uncertainty surrounding sulfate aerosol and black carbon.

Notes: According to the IPCC, the level of scientific understanding is low for sulfate aerosol and very low for black carbon aerosol. The uncertainty estimates in the report are a factor of 2 for each of these substances. (Factor of 2 means, for example, in the case of sulfate aerosol, the upper end of the range would be -0.2, which is half the estimate—the estimate of 0.4 divided by factor of 2—and the lower end of the range would be -0.8, which is twice the estimate—the estimate of 0.4 multiplied by factor of 2.) Note that these uncertainty estimates are not based in statistics, but rather on the range found in the recent literature.

Positive values indicate a warming effect; negative values indicate a cooling effect. The values for black carbon include only the burning of fossil fuels, but not other sources, such as biomass burning, which is estimated to make a similar-sized contribution to warming. Combustion of these substances also emits organic carbon aerosols, which contribute an opposite (cooling) effect on climate. These are all direct effects. Indirect effects, such as those operating through clouds, could increase the impacts of both sulfates and black carbon. Note that these uncertainty estimates are not based on statistical analysis, but rather are subjective judgments based on ranges found in reported studies. In addition, the values for these estimates are described in the IPCC *Third Assessment Report* as having different levels of scientific understanding associated with them: tropospheric ozone—medium; sulfate—low; and fossil fuel black carbon—very low.

These three pollutants are relatively short-lived and are distributed only locally or regionally, in contrast to the traditional greenhouse gases, which persist for many years and are distributed worldwide. In comparison, the effects of the short-lived substances must be averaged over time and space.

Sulfate aerosols. According to the 2001 review, scientists generally agree that sulfate aerosols contribute to cooling the earth. The uncertainty regarding the climate effects of sulfate aerosols is significantly higher than for tropospheric ozone. Because these aerosols are light colored, they do not absorb sunlight. Consequently, their effect is purely cooling, because they reflect sunlight back into space and prevent it from reaching the earth's surface. This cooling phenomenon is referred to as a direct effect on the climate. The total amount of sulfate aerosols in the atmosphere is estimated to be about 10 times larger than the total amount of black carbon aerosols discussed below.

Scientists have also identified indirect cooling effects of sulfate aerosols that result from their effect on clouds. Like some other aerosols, sulfates become the nuclei onto which water vapor condenses, forming cloud droplets. There, they produce clouds composed of larger number of smaller droplets, which result in two indirect effects on the earth's climate. First, smaller droplets tend not to coalesce as readily into raindrops. Therefore, clouds composed of smaller droplets are less likely to produce rainfall and will persist longer. Since clouds scatter solar energy back out to space, they redirect energy away from the earth, causing cooling. Second, since smaller cloud droplets scatter more sunlight per mass than larger cloud droplets, even more solar energy will be directed away from the earth. Because of both the lessened rainfall from affected clouds and the changes in local heating of the earth, with consequent reduction in evaporation, sulfate aerosols can reduce the amount and change the distribution of rainfall in affected areas.

Black carbon. According to the 2001 review, scientists generally agree that black carbon aerosols contribute to warming the atmosphere. As with sulfate aerosols, the uncertainty associated with black carbon aerosols' warming effect is high. Much of the uncertainty about black carbon aerosols' effects is due to questions about how these aerosols mix with other types of aerosols and cloud droplets. In addition, black carbon is released in association with other pollutants, such as organic carbon, which has a cooling effect on climate. The proportions of each can differ substantially among sources.

According to recently completed research on the effect of aerosols in the atmosphere above the Indian Ocean,[10] large amounts of aerosols—including some black carbon—in the air masses coming off the Indian subcontinent lead to dramatic reductions in the amount of solar radiation reaching the ocean's surface and may be reducing precipitation over polluted areas. While these results appear to be significant for a particular geographic area and time period, they have yet to be translated into globally averaged contributions to warming the earth's surface. Nevertheless, they suggest that these aerosols may have a larger effect on warming than was previously recognized.

[10] V. Ramanathan *et al.* "Aerosols, Climate, and the Hydrological Cycle." *Science*, 294, Dec. 7, 2001.

Tropospheric ozone. According to the 2001 review, most scientists agree that tropospheric ozone[11] contributes to warming the earth. The level of uncertainty associated with this warming effect is lower than the level for sulfate aerosols and black carbon but is greater than for carbon dioxide and other well-mixed greenhouse gases. However, ozone is not uniformly distributed throughout the troposphere because it is produced in a very uneven pattern in polluted areas and has a shorter lifetime than most other greenhouse gases. As figure 2 shows, its estimated warming effect is about one-quarter of the warming effect of carbon dioxide.

The formation of ozone in the atmosphere is complex. Most tropospheric ozone is generated by gases, called ozone precursors, that are emitted by industry, automobiles, and some natural sources, such as lightning and soil. There are two main classes of ozone precursors: nitrogen oxides (made up of nitric oxide and nitrogen dioxide) and certain carbon-containing gases, such as carbon monoxide and volatile organic compounds, including methane. Recent research suggests that reducing methane could have a greater effect in reducing ozone than previously recognized.[12,13] This discovery is significant, since methane, unlike the other ozone precursors, lasts in the atmosphere for as long as 10 years. (See fig. 1.)

[11] Ozone in the stratosphere also has impacts on climate. It is formed by different means than ozone in the troposphere. We do not discuss stratospheric ozone at length in this report because it is produced mainly through natural (non-human-induced) processes. Ozone in the troposphere exists in two zones, the boundary layer and the free troposphere. The significance of these zones is explained in the next section.

[12] Arlene Fiore *et al.* "Linking Air Pollution and Climate Change: The Case for Controlling Methane." *Geophysical Research Letters*, 29(19), 1919, 2002.

[13] Michael Prather *et al.* "Fresh Air in the 21st Century?" *Geophysical Research Letters*, 30(2), 1100, 2003.

The Three Pollutants Are Generally Declining in Economically Developed Countries, but Not in Developing Countries; All Seven Countries Are Acting to Reduce Emissions

The seven countries we reviewed have all enacted legislation and implemented regulations to reduce emissions of sulfur dioxide[14] and black carbon, and concentrations of tropospheric ozone.[15] For the most part, the levels of the three pollutants are declining in the four economically developed countries and, to a limited extent, in the three economically developing countries.

Our analysis of measures to control emissions and concentrations of these substances is organized by pollutant; for each pollutant, we begin with the economically developed countries and then turn to the developing countries. Within the first group, we first discuss the United States because we found the most complete information about it. We next discuss the United Kingdom, Germany, and Japan, in declining order of available information. For economically developing countries, for similar reasons, the order is China, India, and Mexico.

Sulfur Dioxide Emissions Declined in Nearly All Countries; All Seven Countries Are Taking Steps to Reduce Them

Of the three substances we reviewed, sulfur dioxide was the most widely measured and regulated. Appendix II describes each country's regulatory approach to sulfur dioxide emissions in greater detail.

Developed Countries

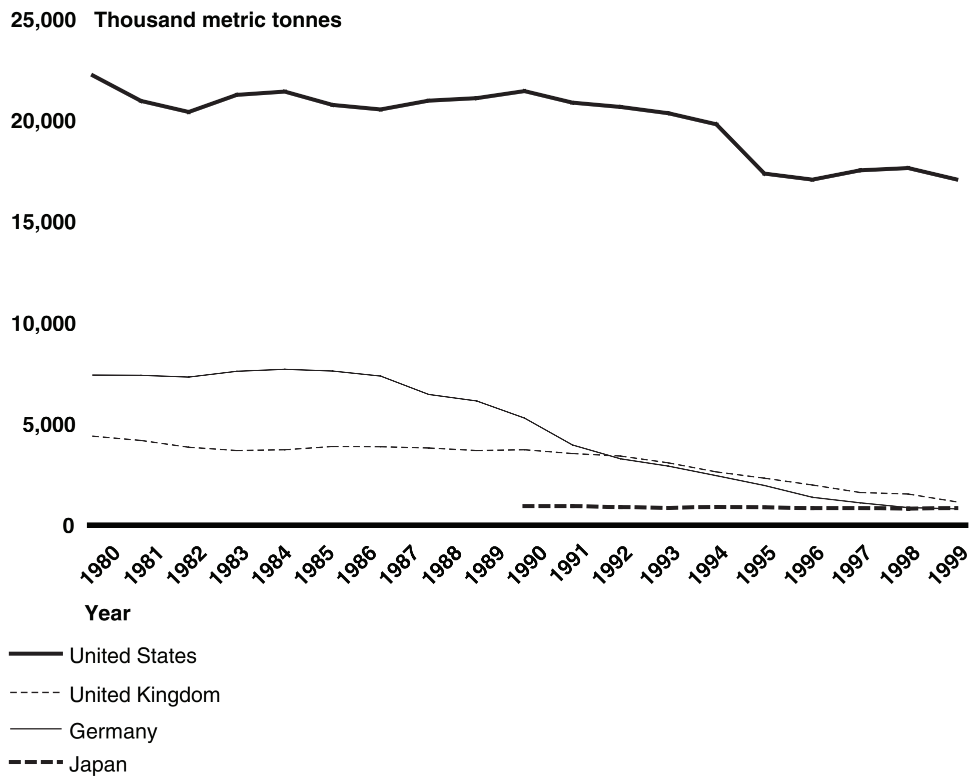
Sulfur dioxide emissions have declined and are expected to continue to decline in the United States, United Kingdom, Germany, and Japan through at least 2010, owing to a combination of explicit government policies designed to curb sulfur dioxide emissions, the development of cleaner power generation and transportation technologies, and a continuing transition in many countries away from high-sulfur coal to low-sulfur coal and natural gas. Figure 3 shows the decline in emissions for the United States, the United Kingdom, and Germany between 1980 and 1999

[14] In this report, we use sulfur dioxide emissions as a proxy for sulfate aerosols. This is because sulfate aerosols are the result of the chemical transformation in the atmosphere of sulfur dioxide emissions, such as those from power plants and other sources. It is difficult to attribute sulfate aerosols in the atmosphere to individual countries, but such attribution is possible with sulfur dioxide because many countries keep track of their sulfur dioxide emissions.

[15] Because ozone is not emitted directly, it is measured in terms of concentrations.

and for Japan between 1990 and 1999, the only years for which we found data for that country. As the figure shows, the greatest decline occurred in Germany. In most of these countries, emissions declined more steeply between 1990 and 1999 than between 1980 and 1990. Figure 4 shows projected declines between 1990 and 2010 (1995 and 2010 for Japan). As the figure indicates, the greatest relative decline is expected to occur in Germany.

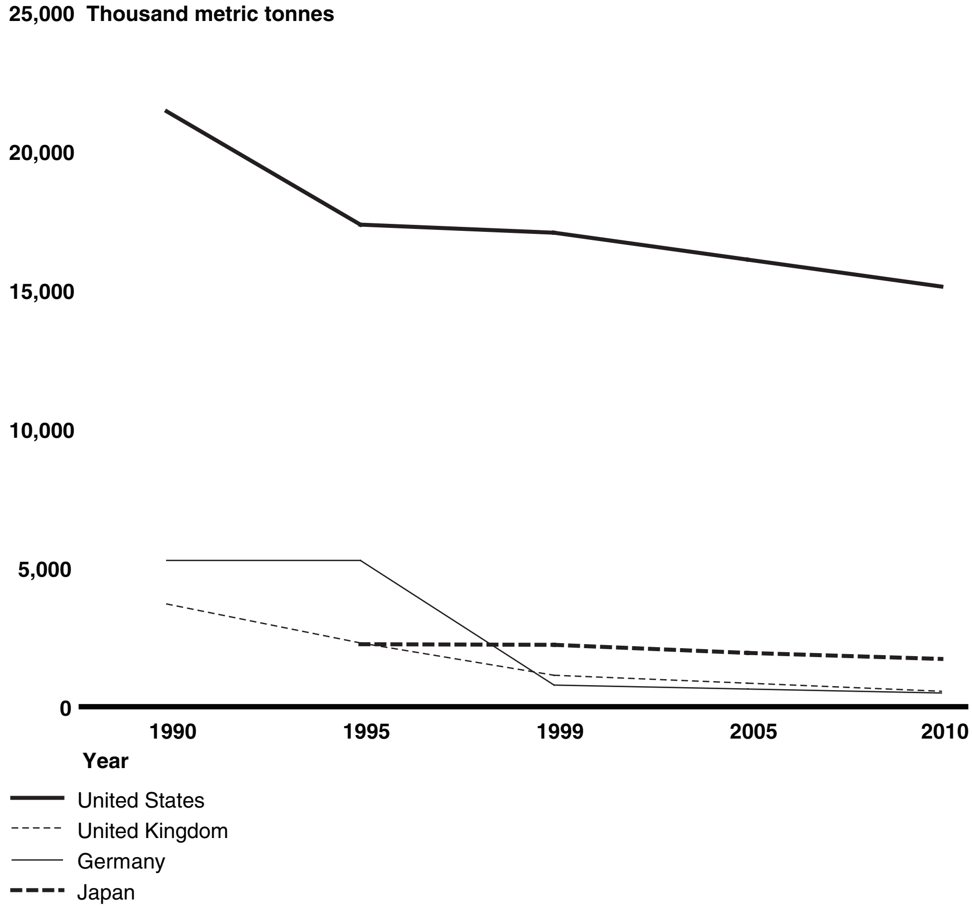
Figure 3: Sulfur Dioxide Emissions in Four Developed Countries, 1980-99



Sources: GAO (graphic); data reported by governments to CLRTAP (U.S., U.K., and Germany) and data reported by the Japanese government in *Japan's Third National Communication to the UNFCCC,* 2002.

Notes: A metric tonne is equivalent to 1.102 short tons (or 2,204 pounds). We were unable to locate data from Japan for 1980 through 1989.

Figure 4: Projected Sulfur Dioxide Emissions in Four Developed Countries, 1990-2010



Sources: Prepared by GAO with data reported to CLRTAP (United States, United Kingdom, and Germany) and data provided by Dr. T. Matsui, Japanese National Institute of Environmental Studies (Japan).

Notes: Projections of U.S. sulfur dioxide emissions do not include recent or proposed EPA rulemakings that are likely to decrease sulfur dioxide emissions in the future. Values from 2000 to 2010 for the United States, the United Kingdom, and Germany are based on 2010 projections.

Both the United States and European countries have health-based standards designed to minimize damage to human health caused by sulfur dioxide emissions. They also have annual emissions limits to control acidification of the environment caused by these emissions. The United States set its limits based on an across-the-board, 50-percent reduction in sulfur dioxide emissions, relative to 1980, from power plants. In contrast, the European governments set their standards using the "critical loads" approach, taking into consideration the estimated potential impact of the emissions on the environment. That is, the Europeans estimate, using mathematical models, the maximum amount of damage that a particular ecosystem—such as forests, lakes, and streams—could sustain before long-term harmful effects occur. Standards aimed at reducing emissions to a level near the critical load goal are then negotiated among countries. This type of standard is often referred to as an effects-based standard. We were unable to find information on how Japan developed its sulfur dioxide emissions standards.

United States. U.S. emissions of sulfur dioxide decreased from 23.5 million metric tonnes to 17.1 million metric tonnes between 1980 and 1999, a decrease of about 27 percent, according to U.S. data submitted to the CLRTAP. The United States projects that sulfur dioxide emissions will decline even further, to 15.1 million metric tonnes in 2010, representing about a 36-percent decrease from 1980 levels (See fig. 4.) The decline in emissions in 2010 may be even greater because U.S. projections take into account only national policies but not state regulations. They also do not include proposed new measures.

Sulfur dioxide emissions started to decline in the United States in the early 1970s, after peaking at about 31 million tons. Federal regulation of sulfur dioxide emissions essentially began with the Clean Air Act of 1970, as amended in 1977 and 1990. The act required the Environmental Protection Agency (EPA) to develop national air quality standards for air pollutants that may endanger public health and welfare. EPA established such standards for sulfur dioxide and several other pollutants. The act also required each state to develop a plan (to be approved by EPA) for meeting those standards. Under the act, all new or modified large power plants could emit no more than a specified rate of sulfur dioxide per unit of fuel consumed. Most new plants responded to this requirement by shifting to coals with lower sulfur content.

Concern about sulfur dioxide emissions increased again in the late 1970s and early 1980s, when scientists noticed that lakes and streams, particularly in the Northeast, were becoming increasingly acidic, thereby threatening aquatic life. This acidity was traced to sulfur dioxide and nitrogen oxide emissions from power plants, primarily those located upwind in the Midwest. The 1990 Clean Air Act Amendments imposed additional controls on such emissions. One of the programs created under the amendments was the Acid Rain Program, which employs emissions trading, a market-based mechanism, to reduce sulfur dioxide emissions.

United Kingdom. According to data submitted to the CLRTAP, the United Kingdom reduced its sulfur dioxide emissions from just under 4.9 million metric tonnes in 1980 to about 1.2 million metric tonnes in 1999, a decrease of about 75 percent. The majority of the reduction was due to an increase in the use of nuclear and renewable energy, fuel-switching (e.g., to natural gas), improvements in efficiency, flue gas desulfurization,[16] and fuel sulfur reductions. The United Kingdom projects that its sulfur dioxide emissions will decline even further, from about 1.2 million metric tonnes in 1999 to 0.6 million metric tonnes in 2010, an additional decrease of nearly 50 percent. If realized, this decrease would represent an 87-percent reduction from the 1980 level.

Sulfur dioxide emissions, along with other pollutants, contributed to several major smog episodes in London during the first 6 decades of the 20th century, with the most significant one occurring in December 1952. That episode took more than 4,000 lives over 5 days. It also led to the enactment of legislation in 1956 and 1968 that aimed to reduce emissions from households. A 1990 law gave the government the power to set emissions limits and environmental quality standards for industrial plants. A 1995 law introduced a new framework for air quality policy, giving added prominence to the concept of air quality standards.

In addition, the United Kingdom has international obligations to reduce sulfur dioxide emissions. As a party to the CLRTAP, the United Kingdom intends to reduce its annual emissions of sulfur dioxide by at least 80 percent by 2010 from its 1980 level. Furthermore, it must comply with EU requirements to reduce sulfur dioxide emissions. (See app. II.)

Germany. According to data submitted under the CLRTAP, sulfur dioxide emissions in the unified Germany declined by nearly 85 percent, from 5.3 million metric tonnes to 0.83 million metric tonnes between 1990 and 1999. This decline resulted from such factors as the post-1990 economic restructuring, the retirement of outdated plants in the former East Germany, and the use of less sulfur-intensive fuels. Germany reports that it expects to reduce its sulfur dioxide emissions by about 34 percent between 1999 and 2010.

[16] Flue gas desulfurization equipment removes sulfur oxides from the combustion gases of a boiler plant before it discharges them to the atmosphere.

West Germany began to regulate sulfur dioxide in the late 1970s, when it signed the CLRTAP. It participated in this effort in part out of concern that sulfur dioxide-induced acidification was killing large numbers of trees in the forests of southwestern Germany.

West Germany's emissions of sulfur dioxide declined markedly during the 1980s, mainly because utilities expanded their use of natural gas to generate electricity, installed flue gas desulfurization technology in power plants, and substituted less sulfur-intensive fuels at power plants and in industry. In contrast, emissions in the former East Germany rose until 1987, mainly because utilities there used lignite (low-grade coal) to generate electricity.

Germany's primary legislative instrument to control sulfur dioxide and other air emissions is a 1974 law, amended in 2000, that regulates emissions from both large and small combustion facilities. Supporting ordinances contain detailed regulations and emissions limits for all facilities covered by the act. Germany is also reducing its sulfur dioxide emissions under both the CLRTAP and EU directives.

Japan. According to the Japanese government, sulfur dioxide emissions declined by about 9 percent between 1990 and 1999, or from 0.97 million metric tonnes to 0.87 million metric tonnes. According to another source—a researcher from the Japanese government's National Institute for Environmental Studies—sulfur dioxide emissions may decline by 27 percent between 1995 and 2010.[17]

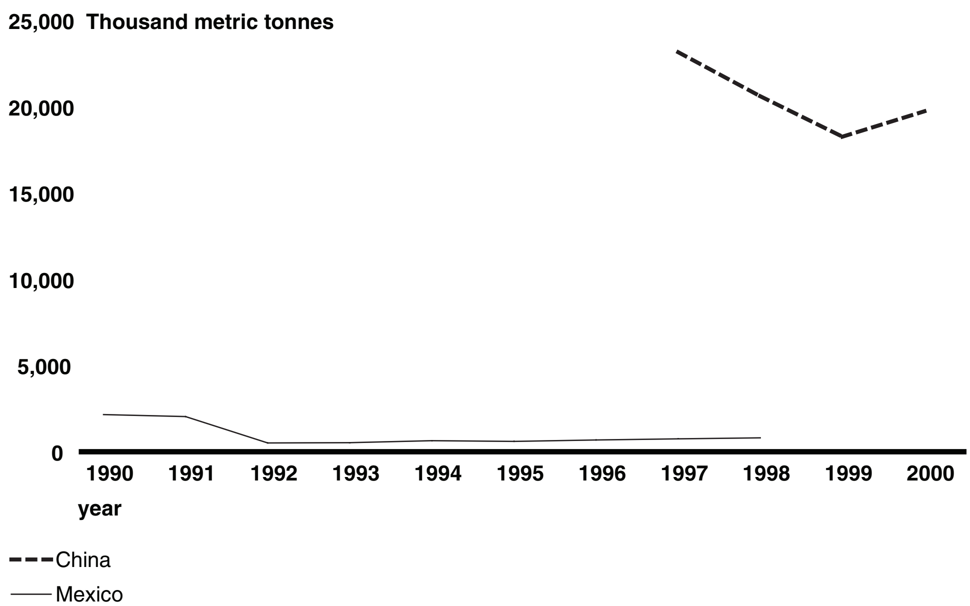
Compared with other industrialized countries, particularly the United States and Germany, Japan uses considerably less coal, relying instead on nuclear power to generate one-third of its electricity. Nevertheless, in 1968, Japan began to regulate sulfur dioxide and other substances created by fuel combustion. It set standards for emissions from power plants and factories and provided for stations in several parts of the country to monitor emissions of sulfur dioxide and other substances. In the late 1970s, the government required facilities to install scrubbers in their smokestacks. Japan also reduced its sulfur dioxide emissions through gains in combustion efficiency and a transition to low-sulfur coal.

[17] Four scenarios with reductions ranging from 7 to 37 percent were prepared by Dr. T. Matsui for the United Nations Environment Program. The data for Japan in figure 4 show projected emissions reductions in 2010 from an intermediate scenario.

Developing Countries

As in the developed countries, China and Mexico saw an overall decrease in sulfur dioxide emissions during the 1990s, as shown in figure 5. We were unable to find data for India. Sulfur dioxide emissions in China declined by 15 percent between 1997 and 2000, in part as a result of the combination of emission reduction policies and a decline in coal use. However, emissions increased slightly after 1999. According to Mexico's National Greenhouse Gas Inventory, sulfur dioxide emissions decreased by about 55 percent between 1990 and 1998, though they increased very slightly between 1993 and 1998. We were unable to find consistent historical data on sulfur dioxide emissions in India. We were also unable to find data on projected emissions levels for any of these three countries. According to U.S. experts, the quality of some of the data for these countries is uncertain, due in part to old measuring equipment and techniques.

Figure 5: Sulfur Dioxide Emissions in China and Mexico, Selected Years



Sources: GAO (graphic); data reported by the Chinese State Environmental Protection Administration and the *Mexican National Greenhouse Gas Inventory, 1994-1998.*

China. China is currently the world's largest emitter of sulfur dioxide. It relies heavily on coal as an energy source, and the country's sulfur dioxide emissions rose initially along with rapid industrialization. More recently, according to the Chinese State Environmental Protection

Administration, emissions of sulfur dioxide declined from 23.4 million metric tonnes to 20 million metric tonnes between 1997 and 2000.

Although under its current 5-year plan (2001-2005), China aims to reduce coal consumption by increasing the share of natural gas and renewable energy in the total energy supply, the U.S. Department of Energy's Energy Information Administration (EIA) projects that coal combustion in China will increase 60 to 194 percent between 1999 and 2020, depending on assumptions about economic growth. Thus, sulfur dioxide emissions could also rise, unless implementation of a 1987 Air Pollution Control Law, amended in 2001, can slow or reverse this trend. The law is designed to improve air quality in large- and medium-sized cities through stiffer penalties, better enforcement, and greater use of market-based methods, such as the imposition of sulfur dioxide discharge fees. It also provides incentives for using high quality, low sulfur coal and requires new or expanded sulfur dioxide-emitting power plants and large- and medium-sized enterprises to install sulfur dioxide scrubbing equipment.

India. We found limited data on India's sulfur dioxide emissions. Specifically, we found estimates from one source for 1980 and 1990, which showed an 82-percent increase. We found an estimate from another source for 2000 alone, which is higher than the 1990 estimate from the other source. However, because these sources used different estimating methods, their results may not be comparable.

We were also unable to find sulfur dioxide projections for India. However, the EIA projects that India's coal consumption will increase 9 to 62 percent between 1999 and 2020, depending on assumptions about economic growth. It also notes that, because of shortages in generating capacity and public funds, India will probably continue to rely on old, coal-fired plants for some time, despite their contribution to the country's air quality problems.

Coal accounts for more than half of India's primary fuel consumption, but the sulfur content of the coal used is relatively low. Nevertheless, India has undertaken some steps to reduce sulfur dioxide emissions from coal. For example, it has improved the combustion efficiency of conventional coal technologies and has promoted the use of renewable energy technologies as an alternative to coal. It further adopted national air quality standards for sulfur dioxide and other pollutants in 1982 and revised them in 1994. India has also reduced the sulfur content of oil products. According to the EIA, India's high levels of pollution do not result from a lack of effort in building a sound system of legislation and regulation, but rather from weak enforcement at the local level.

Mexico. According to the Mexican government, sulfur dioxide emissions decreased by 67 percent between 1990 and 1992, but started to increase gradually after 1992. Between 1990 and 1998, however, the net decrease was 55 percent. We were unable to find data on projected sulfur dioxide trends. However, Mexico has considerably expanded its use of natural gas, which produces less sulfur than coal, and according to a 2002 report by the EIA, most new power plants in Mexico are likely to be gas-fired, although some new coal-fired plants will also be constructed. EIA projects that coal consumption will grow 62 to 115 percent between 1999 and 2020, depending on assumptions about economic growth. Most of Mexico's energy comes from oil, with coal providing only about 4 percent of the country's energy requirements.

The basic law for reducing air pollution emissions is the 1988 General Law of Ecological Equilibrium and the Protection of the Environment. The law provides the framework for air pollution standards for all major substances. Environmental protection became a particularly important issue for Mexico in the early 1990s as a result of negotiations for the North American Free Trade Agreement with the United States and Canada. In 1992, the Mexican government created a special office to enforce regulations. This office is charged with inspecting facilities and issuing penalties for noncompliance. According to Mexican government officials, Mexico's limited financial resources prevent full enforcement of environmental regulations, despite steadily improving enforcement efforts. Mexico has also introduced a federal tax incentive program for purchasers of pollution control equipment. In addition to national legislation, some air quality initiatives are underway in large cities, where urban air pollution is a significant problem.

Black Carbon Emissions Generally Declined in Developed Countries and Generally Increased in Developing Countries

Scientists have begun to recognize the importance of black carbon as an agent of climate change only within the past few years. Consequently, most countries do not directly track emissions of this pollutant. Therefore, to conduct our analysis, we used a global black carbon database developed by atmospheric researchers.[18] This database has several limitations. First, as with most emissions inventories, estimates in this database are not based on actual black carbon measurements, but rather are calculated using information on countries' use of fossil fuel, which is measured, along with estimates of how the fuel is used. Second, this database does not contain historical information on open biomass burning (forest burning or land-clearing), which may account for as much as 50 percent of black carbon emissions. Finally, emissions estimates are based on limited information about the characteristics of the fuels and technologies that produce the emissions.

Black carbon emissions are particularly difficult to track because they are often produced by activities that are informal and unregulated, and in developing countries, there is considerable consumption of noncommercial fuels, such as wood or animal waste. Since these fuels are not reported the same way as fossil fuels, neither the amounts used nor the emissions produced are well quantified. Because sophisticated emission measurements have usually been available only in developed countries, moreover, there are few measurements of the combustion that produces most black carbon emissions in developing countries. For these and other reasons, the black carbon emissions data are highly uncertain. Despite these weaknesses, this database is currently the only source we found that contained consistently estimated information on different countries' emissions.

[18] T.C. Bond and D.G. Streets, "Draft Global Black Carbon Inventory," 2002. Dr. Tami Bond, Visiting Scientist, National Center for Atmospheric Research, and Dr. David Streets, Senior Scientist, Argonne National Laboratory, provided both data and commentary on this section.

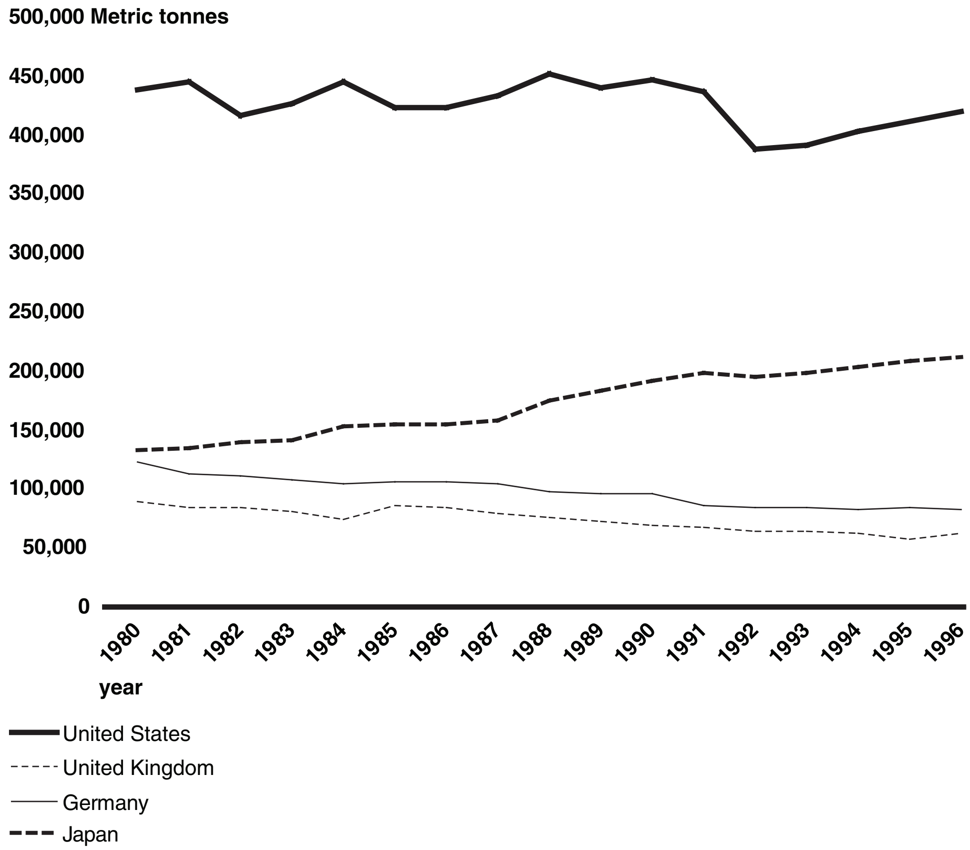
Black carbon usually comes from the same sources as organic carbon, which has a cooling effect on climate. It would be difficult to control emissions of either substance separately; hence, it would therefore be difficult to control warming by reducing black carbon emissions. Although countries do not regulate black carbon directly, it is one component of what regulatory agencies often refer to as particulate matter,[19] and most of the countries we reviewed do regulate particulate matter. We therefore collected information on measures to reduce particulate matter, recognizing that this pollutant is an imperfect proxy for black carbon. Furthermore, even when particulate matter emissions are reduced, black carbon levels may not decline because some types of particulate matter, such as sulfate, do not contain black carbon when emitted.

Developed Countries

According to the database we used, the majority of black carbon emissions in developed countries results from the combustion of diesel fuel by vehicles, including both on-road vehicles, such as heavy-duty trucks, and off-road vehicles, including farm and construction equipment. As figure 6 shows, black carbon emissions from fossil fuel combustion declined in three of the four developed countries, more in the United Kingdom and Germany and less in the United States. During this period they increased in Japan, starting in the early 1980s. (See app. III for more detail on policy measures to reduce black carbon emissions.)

[19] Particulate matter is the general term used for a mixture of solid particles and liquid droplets found in the air. It comes from vehicle emissions, dust, fires, sea salt, and black carbon (soot) from wood and coal burning. Particulate matter can be either coarse or fine. Coarse particulate matter is referred to as PM_{10} because the particles have a diameter of 10 micrometers or less. Fine particles, referred to as $PM_{2.5}$, have a diameter of 2.5 micrometers or less. Black carbon is a component of $PM_{2.5}$, but this fraction may vary across countries, depending on fuel sources. Secondary particles can be formed in the atmosphere from gaseous emissions. For example, sulfates are a form of particulate matter.

Figure 6: Black Carbon Emissions in the United States, United Kingdom, Germany, and Japan, 1980-96



Source: GAO (graphic), T.C. Bond and D.G. Streets (data).

Note: Graphic based on global black carbon database prepared by T.C. Bond and D.G. Streets for an article entitled, "A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion," to be submitted to the *Journal of Geophysical Research*.

United States. According to the database we examined, black carbon emissions in the United States were approximately 4 percent lower in 1996 than in 1980. However, there was a steady increase from 1992 to 1996. According to this database, about one-half of black carbon emissions in the United States are from the use of diesel vehicles to transport goods over long distances and from off-road diesel vehicles. However, the database may not fully reflect the effects of certain technologies that were introduced in the 1990s to reduce diesel emissions. Including such technologies in the database would likely show greater emissions declines during the 1990s. Gasoline-fueled cars and wood combustion in home fireplaces and stoves are other, smaller sources of black carbon emissions.

The United States is the only country for which we found projections of black carbon emissions. These were developed in support of an EPA rulemaking[20] relating to large trucks. When the rule is fully implemented in 2030, black carbon emissions are expected to decrease by an estimated 109,000 tons from the level produced in 1996.[21]

The United States has several efforts underway to help reduce emissions of black carbon and other types of particulate matter. Under the Clean Air Act, EPA promulgated national air quality standards for particulate matter in 1971 and has regulated particulate matter emissions from highway motor vehicle engines. The most recent rule is designed to reduce emissions from heavy-duty diesel vehicles by improving diesel engines and reducing the sulfur content of diesel fuel.[22]

United Kingdom. According to the database we used, black carbon emissions from the United Kingdom declined by about one-third between 1980 and 1996. The sources of black carbon emissions in the United Kingdom are similar to those in the United States, with the majority of emissions produced by diesel vehicles. Other sources of black carbon emissions are industrial coke-making[23]and coal-burning in the residential sector, although residential coal use is declining in the United Kingdom.

The Parliament enacted legislation in 1956 and 1968 to control domestic sources of particulate matter. The 1956 act aimed to control domestic sources of smoke pollution by introducing smokeless zones (regions where smokeless fuel had to be burned) and by making grants to homeowners to convert their homes from traditional coal fires to heaters fueled by oil, gas,

[20] The 2002 Heavy-duty Diesel Engine Rule is aimed at reducing emissions from heavy-duty trucks.

[21] EPA's estimate of black carbon emissions for 1996 differs from that found in the Bond and Streets database. This is because estimates from the two studies are based on different assumptions.

[22] The sulfur content of diesel fuel is important because sulfur can impair the performance of a vehicle's emissions-reducing device.

[23] Coke is a solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal. It is used as a fuel (and as a reducing agent) for smelting iron ore in blast furnaces.

smokeless coal, or electricity. Legislation in 1990 and 1995 brought many smaller emission sources under air pollution control by local authorities for the first time. These acts also provided a new statutory framework for local air quality management. In 1997 the United Kingdom published its first national air quality strategy, which set air quality standards and objectives for the pollutants of greatest concern, including particulate matter. The United Kingdom changed the particulate objective under this strategy in 2000, in response to a new EU directive and then in 2002 strengthened the objective once more.

In the transportation sector, the EU in 1992 introduced directives containing exhaust emission limits (generally referred to as the Euro I standards) for new medium- and heavy-duty diesel engines. The standards aimed to reduce emissions of particulate matter, as well as carbon monoxide, hydrocarbons (including volatile organic compounds), and nitrogen oxides, all ozone precursors. More stringent emission limits for these vehicles, called Euro II, came into effect in 1996. Euro III limits were adopted in 1999, and even more rigorous standards for these vehicles, Euro IV and Euro V, are expected to take effect in 2005 and 2008, respectively. The EU also set standards in 2001 for maximum allowable levels on the sulfur content of diesel fuel. The directive, effective January 1, 2005, will introduce sulfur-free diesel and gasoline in all EU member states.

Germany. Black carbon emissions in Germany also declined by about one-third between 1980 and 1996, according to the Bond and Streets database. While diesel consumption and emissions increased rapidly during this time, a phase-out of coal combustion for home heating led to an overall reduction in black carbon emissions. Other large sources of black carbon emissions in Germany—much smaller than diesel vehicles—are industrial coking coal and gasoline vehicles.

Between 1990 and 1996, Germany decreased its emissions of particulate matter by 86 percent. The decrease occurred primarily because of developments in eastern Germany after reunification, when many older industrial and power plants were closed or refitted with new technologies that remove soot particles. In addition, many installations shifted to the use of gas and liquid fuels—especially in small combustion appliances—thereby producing less particulate matter. The Federal Emission Control Act provides the framework for regulating all air pollutants, and its ordinances govern both large and small combustion facilities.

Like the United Kingdom, Germany must abide by EU directives aimed at reducing particulate matter emissions, including the Euro I–III directives on diesel vehicle emissions. Most diesel vehicles currently emit much less particulate matter than earlier models, but Germany is continuing its effort to reduce emissions in the transportation sector. For example, in 2001 Germany passed legislation to offer tax breaks for sulfur-free gasoline and diesel fuel starting this year.

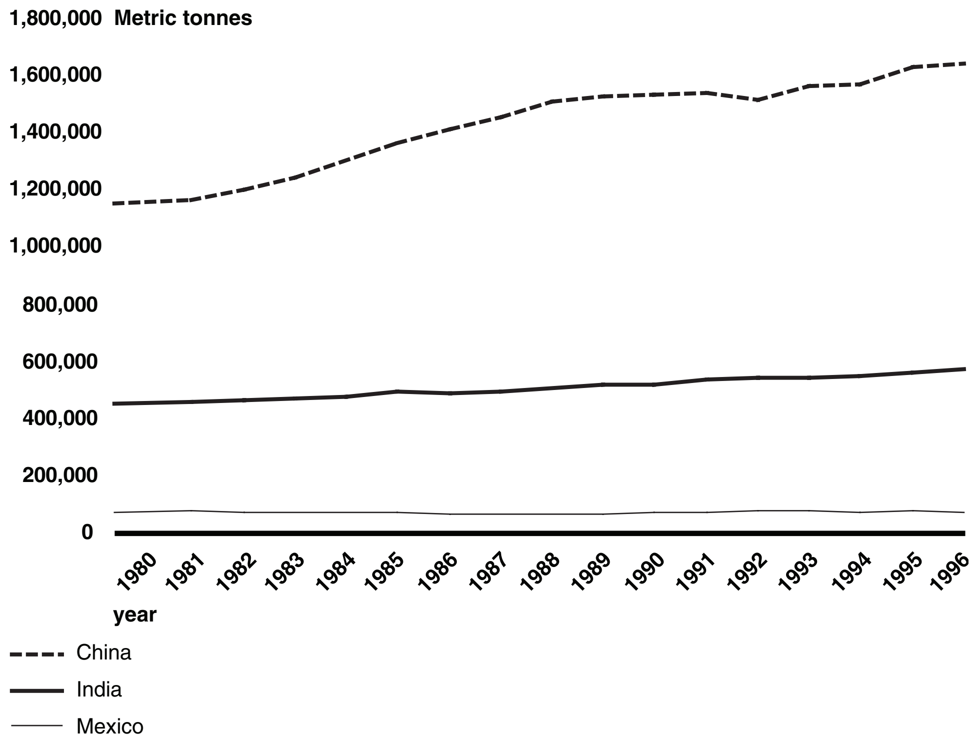
Japan. Black carbon emissions in Japan were about 60 percent higher in 1996 than in 1980, according to the database we used. The major source of these emissions is diesel fuel, the use of which began to increase in 1988. As in the United Kingdom and Germany, coke-making could be an additional source of black carbon emissions in Japan.

In June 2001, Japan's legislature enacted a law to further tighten particulate matter emissions from diesel-powered vehicles to improve air quality in major urban areas. The law applies to 196 local governments in Tokyo, Osaka, and four other cities.

Developing Countries

The database we used indicates that black carbon emissions increased between 1980 and 1996 in China and India, as figure 7 shows. It suggests that Mexico's black carbon emissions are essentially unchanged over this period. We found no projections of black carbon for any of these three developing countries.

Figure 7: Black Carbon Emissions in China, India, and Mexico, 1980-96



Source: GAO (graphic), T.C. Bond and D.G. Streets (data).

Note: Graphic based on global black carbon database prepared by T.C. Bond and D.G. Streets for an article entitled, "A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion," to be submitted to the *Journal of Geophysical Research*.

China. Emissions of black carbon in China rose by 43 percent between 1980 and 1996, according to the Bond and Streets database. Moreover, according to that data source, China emits more black carbon than any other nation in the world—approximately 29 percent of the global total. However, its per capita emissions are not higher than those of other countries. These emissions came primarily from coal (especially dirty soft coal) and wood in the residential sector, coal-burning power plants using older technologies, on-road and off-road diesel vehicles, and coke-making plants in the industrial sector. Emissions increased steeply in the 1980s, but the growth rate slowed somewhat in the 1990s as China began to switch from coal to cleaner natural gas and from raw coal to coal briquettes (which produce fewer emissions) in the residential sector; it also closed many small industrial coal plants.

Under amendments in 2000 to its Air Pollution Control Law, the government set a goal of reducing “soot and flue dust” (particulate matter) emissions to 1995 levels by 2010. According to the law, new or expanded power plants and large- and medium-sized industrial facilities must install particulate matter control equipment or take other measures to reduce emissions. The city of Beijing requires the use of gas in place of coal in new fuel applications.

In the transportation sector, China has implemented emissions standards for diesel vehicles. In 2000 and 2001 the government introduced the Euro I emissions standards for new cars and trucks. The standards, which apply to the entire country, are based on those standards originally introduced in Europe in 1992 and limit the amount the amount of particulate matter and other substances that can be emitted from new diesel vehicles. More stringent Euro II norms currently apply to Beijing and Shanghai and will apply to the entire country after 2005.

India. According to the database we used, black carbon emissions in India rose by just under one-third between 1980 and 1996. Most of this country’s emissions come from the use of biofuel in the residential sector, with diesel vehicles contributing a smaller, but noticeable, fraction. Black carbon emissions increased between 1980 and 1996, as the population grew and burned more wood, dung, and agricultural waste for cooking and home heating.[24] The Environmental Protection Act of 1982 set national standards for the emissions of various substances. The standards were revised in 1994. Revisions to the act in 1996 set fuel quality specifications, including requirements for low-sulfur diesel. In the capital city of New Delhi, 84,000 public vehicles were converted from gasoline and diesel to compressed natural gas, which emits negligible particulate matter. In 2000, the Indian government introduced Euro I standards for private, non-commercial vehicles throughout the country. Euro II norms currently apply to New Delhi and will apply to the entire country after 2010.

Mexico. Black carbon emissions in Mexico remained fairly constant between 1980 and 1996, according to the database we used. Mexico is not a large consumer of coal, instead relying primarily on oil as its key energy source. Most of its black carbon emissions come from diesel fuel use.

[24] Levels of emissions from biofuels are particularly uncertain because data are so sparse. Estimates in the Bond and Streets database are calculated based largely on a limited number of fuel use surveys combined with socioeconomic data.

However, according to a Mexican government official, in rural areas, villagers burn propane or biomass for home cooking; biomass produces black carbon emissions. Older gasoline cars also produce black carbon emissions in Mexico.

Trends in Surface Ozone Concentrations Are Mixed, but Background Ozone Levels in the Troposphere Appear to Be Rising, With Implications for both Air Quality and Climate

The earth's weather takes place in the lowest layer of the atmosphere, called the troposphere, which extends from the earth's surface to between 9,000 and 16,000 meters above the surface. Within the troposphere, ozone concentrations differ between zones,[25] the boundary layer, which extends from the earth's surface to roughly 500 to 3,000 meters above the earth's surface, and the much larger free troposphere. (The height of the boundary layer can vary by time of day and season: higher in the daytime and in summer, and lower in winter and at night.) Ozone in these two zones has different durations and effects. There are important interactions between the two zones.

Ozone in the boundary layer generally results from human activity, such as transportation and fossil fuel combustion. Peak ozone episodes usually occur in the summer months, under conditions of long periods of bright sunshine, warm temperatures, light winds, and abundant ozone precursors. Changing weather patterns contribute to yearly differences in ozone concentrations from region to region.

Boundary layer ozone lasts only a few days over land, where it gets deposited on surfaces. Over large bodies of water, such as oceans, it can last longer, since there are no surfaces for deposition. At high concentrations ozone can contribute to human respiratory problems and plant damage.

[25] Dr. Loretta J. Mickley, Research Associate, Atmospheric Chemistry, Division of Engineering and Applied Sciences, Harvard University, and Dr. Michael Prather, Fred Kavli Chair and Professor, Department of Earth System Science, University of California Irvine, provided insights and comments on this section.

The free troposphere is much larger than the boundary layer and extends several miles above the boundary layer to the top of the troposphere. Ozone in the free troposphere consists of some naturally occurring ozone (such as ozone produced by lightning and ozone descending from the stratosphere), as well as human-generated ozone carried upward from the boundary layer by wind. Ozone in the free troposphere generally lasts longer than ozone in the boundary layer—from 1 to several weeks.[26] In the free troposphere, ozone, like other greenhouse gases, can trap surface radiation and contribute to warming the earth.

Air is exchanged extensively between the boundary layer and the free troposphere. Consequently, ozone pollution arising from the boundary layer—particularly in the northern hemisphere—has contributed to increased levels of ozone in the free troposphere. Hence, the troposphere—the source of clean air at the earth's surface—is showing an increasing background level of ozone.[27] With the higher concentrations of ozone in the free troposphere and in remote regions, more ozone can be blown into populated areas, worsening the local pollution. Ozone pollution has also been carried to the surface over remote regions, such as the oceans and the Arctic.

Current estimates of ozone concentrations are based on profiles from ozone balloons equipped with measuring devices (sondes). However, these sondes are released from locations that are sparsely distributed around the globe. Because the information from the sondes is so limited, we used two types of proxy data to illustrate trends in the free troposphere, where ozone can affect the climate. First, we used historical data on ozone at the surface, which regulatory agencies, such as EPA, gather for air quality purposes. These data are measured at a network of monitoring stations, mainly in developed countries, and are collected primarily from urban and suburban areas, where ozone is a major health concern. Second, we used the results of a global modeling study that depicts ozone concentrations in the free troposphere.

[26] Ozone has a shorter life span in the boundary layer because processes in that layer can destroy ozone, but these same processes do not occur in the free troposphere. The processes include deposition and chemical destruction at night.

[27] There are various definitions of background ozone. As used in this report, background ozone refers to ozone that is produced by human sources as well as lesser amounts from natural precursor sources—such as volatile organic compounds from vegetation or nitrogen oxides from lightning—that travels into a given jurisdiction from elsewhere and is not associated with local emissions.

Some developed countries have prepared projections of ozone concentrations at the surface, but because ozone projections prepared for air quality purposes do not adequately represent ozone increases in the free troposphere, where it is important for climate, we also used the results of a modeling study from the Harvard University Atmospheric Chemistry Modeling Group.[28] These model results are based on an IPCC scenario that assumes that in 2025 there will be high population growth; significant income disparities between developed and developing countries; continued dominance of fossil fuels, including coal, in developing countries; and some policy measures in place to control ozone precursors. We used these results to represent annually averaged ozone concentrations in the free troposphere over the entire globe in 1990 and 2025. Unlike regional-scale air quality models, such as those used by regulatory agencies, the Harvard model is able to project ozone concentrations in the free troposphere and at a global level, which is of greatest interest for climate change purposes.

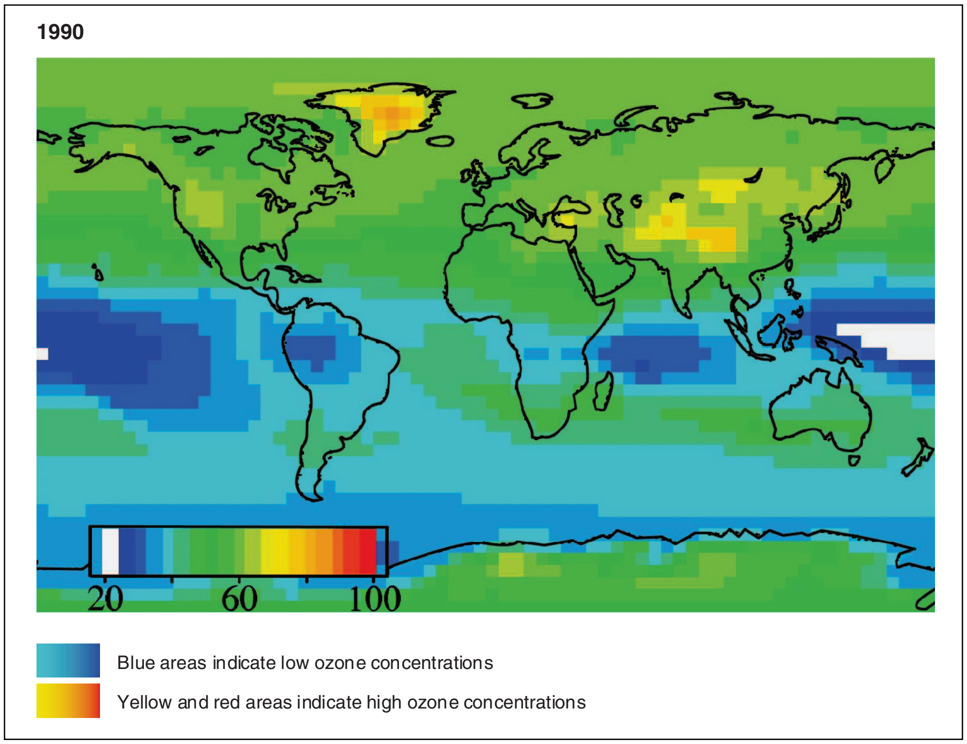
Figure 8 shows calculated ozone concentrations at 5 kilometers (about 3 miles) above sea level for 1990, while figure 9 shows projected concentrations in 2025. Both maps are based on the Harvard model. A comparison of the two maps indicates that free tropospheric ozone levels are expected to increase over the next two decades. Increased emissions of ozone precursors in Asia lead to higher ozone concentrations aloft, with possible consequences for climate change.[29]

[28] We use projections prepared by Dr. L.J. Mickley of Harvard University's Atmospheric Chemistry Modeling Group. The Harvard model has been cited in the IPCC *Third Assessment Report*, a peer-reviewed document. (The IPCC is the premier scientific organization devoted to assessing climate change.) The projections were produced using a general circulation (climate) model and depict expected global average ozone concentrations in the free troposphere in 2025. For comparison purposes, we also include a map showing tropospheric ozone concentrations in 1990. The Harvard projections are based on the IPCC Special Report on Emissions Scenarios (IPCC/SRES) A2 Marker Scenario. The Harvard model is able to capture in great detail the physical and chemical processes leading to tropospheric ozone formation and can also show the long-range movement of ozone and its precursors.

[29] Ozone levels are particularly low over most humid equatorial regions because, over the humid tropics where nitrogen oxide emissions are generally low, water vapor is involved in reactions that destroy ozone.

The most significant of the precursors in this scenario is likely to be methane,[30] also a greenhouse gas, which is projected in the scenario to increase globally by about 20 percent from its present level. Thus, methane poses two problems: it can contribute directly to climate change as a greenhouse gas, and it can indirectly contribute to climate change as an ozone precursor.

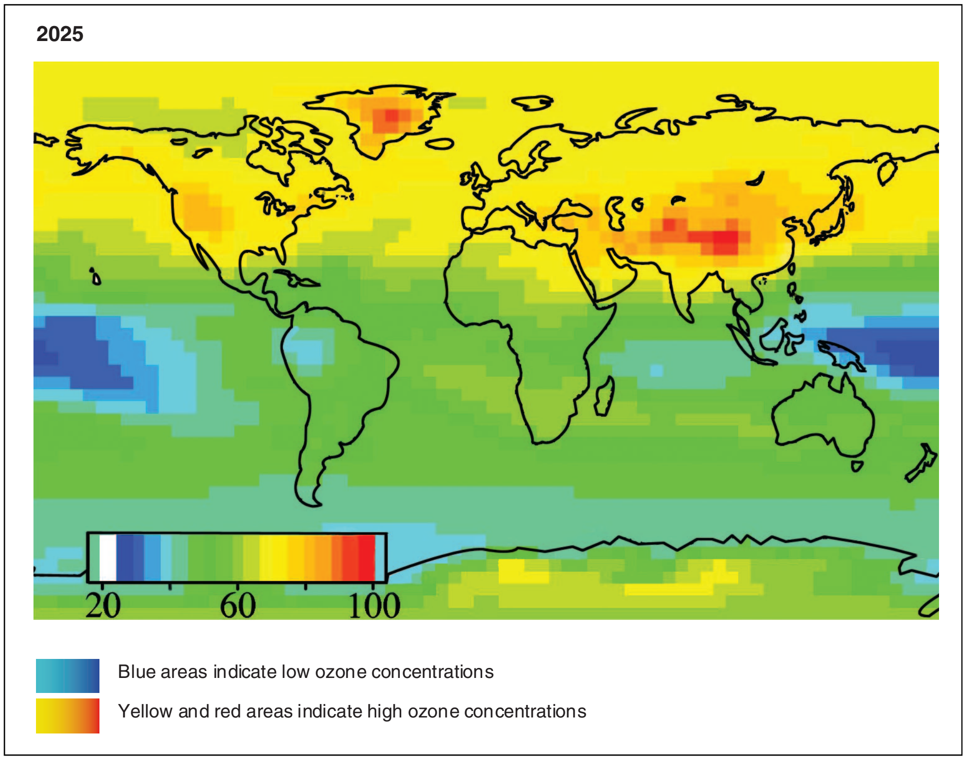
Figure 8: Annually Averaged Global Ozone Concentrations at 5 Kilometers, Parts per Billion, 1990



Source: L.J. Mickley, Harvard University.

[30] Even though global emissions of methane appear to be slowing, it is not clear that they will have dropped sufficiently to result in reduced concentrations in the atmosphere.

Figure 9: Projected Annually Averaged Global Ozone Concentrations at 5 Kilometers, Parts per Billion, 2025



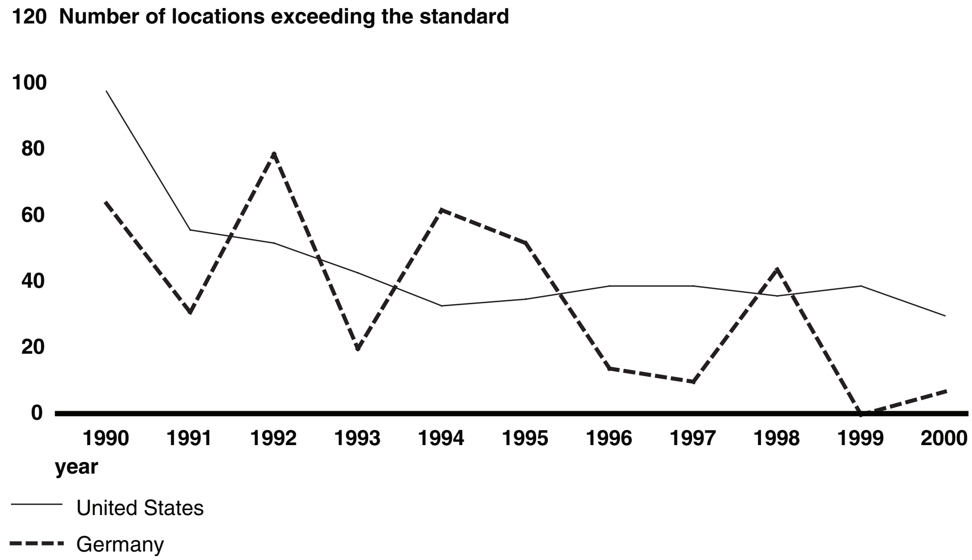
Source: L.J. Mickley, Harvard University.

Developed Countries

Approaches to boundary layer ozone regulation in the United States and Europe differ. The U.S. approach is almost exclusively health-based. That is, its standards are designed to decrease prolonged human exposures to ozone. By contrast, the European approach, as with sulfur dioxide regulation, considers the cumulative effect of ozone concentrations on human health and the environment. It seeks to reduce these concentrations below those levels that affect public health and that can cause long-term damage to the environment. Since the environment can be impaired at lower concentrations than can human health, ozone concentrations associated with European goals are lower than in the United States. While the United States has firm air quality standards for ozone, the EU has non-mandatory target values for ozone concentrations but mandatory emission ceilings for ozone precursors, arrived at after a process that takes both local ozone formation and transboundary transport into consideration. Neither the United States nor most European countries consistently meet their ozone standards in polluted areas. We were unable to find information on how Japan sets its ozone standard.

Cumulative ozone levels in the boundary layer have generally risen over the past century—particularly because of ozone produced in the northern hemisphere. However, some developed countries, such as the United States, the United Kingdom, and Germany, have reported fewer exceedances of their ozone standards over the past decade. That is, peak ozone episodes, in which boundary layer ozone concentrations rise substantially above naturally occurring levels, are becoming somewhat less frequent and extreme in many developed countries. The governments attribute the improvement principally to policy measures over the past decade or so. However, weather conditions and other factors can affect year-to-year changes. Figure 10 shows that the number of locations exceeding their respective ozone standards declined by nearly 70 percent in the United States and by nearly 90 percent in Germany between 1990 and 2000. We were unable to find comparable data for the United Kingdom and Japan. (More detailed information on ozone policies can be found in app. IV.)

Figure 10: Number of Areas Exceeding the Ozone Standard, United States and Germany, 1990-2000



Sources: GAO (graphic) data reported by the U.S. EPA and the German Environment Office.

Note: The U.S. ozone standard trend depicted here is 0.12 parts per million averaged over 1 hour. The U.S. also has an 8-hour ozone standard. The German ozone standard tracked here is 0.055 parts per million averaged over 8 hours.

United States. Under the Clean Air Act of 1970, EPA was charged with developing air quality standards for air pollutants that may endanger public health and welfare. EPA established such standards for ozone and nitrogen oxides, an ozone precursor, in 1971. In 1979 EPA revised the ozone standard to 0.12 parts per million daily maximum over a 1-hour period that is not to be exceeded more than once per year on average. In 1997 EPA tightened the standard to 0.08 parts per million averaged over 8 hours. Although EPA has not yet begun to enforce the new 8-hour standard, it does track concentrations in terms of this standard. According to EPA, national ozone levels decreased 21 percent based on the 1-hour standard and 10 percent based on the 8-hour standard between 1981 and 2000. For 52 metropolitan areas, the trend for 1-hour ozone levels improved between 1981 and 2000. However, beginning in 1994, the rate of improvement started to level off, and the trend since then has been relatively flat.

The U.S. effort to control ozone has focused mainly on reducing emissions of nitrogen oxides and volatile organic compounds, the two classes of ozone precursors. The Clean Air Act requires each state with ozone concentrations above the standard to develop a plan–known as a state implementation plan—for reducing ozone formation; EPA must approve this plan. This reduction can be attained through a mix of regulations in various sectors, such as the utility, transportation, and industry sectors—where most emissions occur. The ozone precursor methane is also controlled under Clean Air Act regulations that require the combustion of certain landfill gases from large landfills.

United Kingdom. According to United Kingdom government data, peak ozone concentrations declined by 30 percent during the 1990s. Emissions of nitrogen oxides declined by 42 percent between 1990 and 1999, while emissions of volatile organic compounds, another ozone precursor, declined by 34 percent between 1988 and 1999. The reductions in precursor emissions are mainly due to stricter regulations, an increasing share of vehicles fitted with catalytic converters (to control nitrogen oxides, volatile organic compounds, and carbon monoxide), and reduced nitrogen oxide emissions from power plants.

Incorporated into the United Kingdom's framework for improving air quality are several measures to address ozone formation. Many of these measures were developed within the framework of the CLRTAP or the EU. For example, in the transportation sector, implementation of the EU's Euro I standards limited emissions of the ozone precursors carbon monoxide, hydrocarbons (including volatile organic compounds), and nitrogen oxides from gasoline vehicles. More stringent standards came into effect in 1997 and 1998, depending on vehicle type, and are known as Euro II. These were superceded by Euro III standards for the majority of vehicles in January 2001. A further tightening of the emissions limits, referred to as Euro IV, will begin in January 2005 and will be fully in force by January 2007.

Certain convention protocols also limit emissions of nitrogen oxides and volatile organic compounds. The United Kingdom also has a domestic target for ozone, which is more stringent than that of the EU.

Germany. According to the German government, peak ozone concentrations have been declining since the mid-1990s. Between 1990 and 2000, emissions of nitrogen oxides declined by 40 percent, and emissions of volatile organic compounds fell by 49 percent. The reductions were due both to regulations—mainly in the transportation sector—and to economic restructuring in the new states of eastern Germany.

Germany, like most other EU countries, has several measures in place for reducing nitrogen oxides and volatile organic compounds, both ozone precursors. These include emission-based motor vehicle taxes on heavy utility vehicles and automobiles and requirements to install advanced emissions reducing devices (that is, catalytic converters) on vehicles. Measures in the utility and industry sectors will also increase the efficiency of fuel combustion to reduce emissions of nitrogen oxides. Germany is bound by the same EU directives and CLRTAP protocols as the United Kingdom.

Japan. According to the Organization for Economic Cooperation and Development, ozone concentrations have increased in urban areas by about 5 percent since the late 1980s. However, according to Japanese data submitted under the United Nations Framework Convention on Climate Change, nitrogen oxide emissions increased by nearly 7 percent between 1990 and 1999, while emissions of volatile organic compounds decreased by just over 3 percent.

In addition to its basic air quality framework, discussed earlier, Japan has several laws targeted at reducing ozone precursors. The 1968 Air Pollution Control Law established standards for photochemical oxidants (ozone) and other substances, including the ozone precursors nitrogen dioxide and carbon monoxide. In 1992 the government introduced the Automobile Nitrogen Oxides Law to tighten controls on nitrogen oxide emissions from vehicles in areas where improvements in emissions were difficult to realize with existing measures. Among other things, the law regulates the types of vehicles that can be driven in areas where nitrogen oxide emissions exceed the environmental standard. The Japanese government has also set emission standards for nitrogen oxides for each industrial facility. The standards vary according to boiler type. Additionally, Japan's air pollution control law regulates volatile organic compound emissions from motor vehicles.

Developing Countries

According to the World Health Organization, some of the poorest air quality in the world, due in part to ozone pollution, is found in Beijing, China; New Delhi, India; and Mexico City, Mexico. However, we were unable to find national data on ozone concentrations for these three countries. China and Mexico monitor ozone only in selected large metropolitan areas. In Mexico City, ozone levels have declined slightly since the early 1990s. We found no information on India. The IPCC reported that emissions of nitrogen oxides—an ozone precursor—in East

Asia are increasing by about 4 percent per year. This suggests that ozone levels may rise along with continuing industrialization in that region.

China. Vehicle emissions are one of the major sources of air pollution in China's major cities. The country currently has over 40 million vehicles, and the number is growing by 10 percent annually; in large cities the rate of growth is even higher. The Euro I vehicle emissions standards in place around the country limit levels of carbon monoxide, hydrocarbons, and nitrogen oxides. The Euro II standards, in place in Beijing, aim to further reduce vehicle emissions in that metropolitan area.

Mexico. Efforts are underway to reduce emissions in the transportation sector, particularly in Mexico City. Since 1993, the Mexican government has increased its efforts to inspect motor vehicles. As of 2001, 230 new car models had undergone emissions inspections. Another program reduces the number of cars on the road in Mexico City and provides incentives for the purchase of cars with lower emissions.

India. As in China, India's Euro I and II performance standards for automobiles are designed to help reduce emissions of key vehicle-related ozone precursors.

Studies of the Effect of Economic Growth on the Environment Are Inconclusive

Both empirical and theoretical studies on the possible connection between economic development and environmental quality are inconclusive overall. Empirical studies, which analyze historical data for possible connections between economic growth and environmental quality, have found that emissions for some substances initially increase as national income rises and then decrease as a certain level of income is reached. However, these results are not consistent across all studies and for all substances.[31] Similarly, theoretical studies, which seek to understand the relationship between economic growth and environmental quality, do not agree on the major factors underlying this relationship. While acknowledging a probable relationship between economic growth and environmental quality, the authors of these studies caution that economic growth does not automatically result in environmental improvement. They explain that, while economic growth may enable countries to pay for environmental protection, growth is not by itself sufficient to reverse environmental

[31] Carbon dioxide is not regulated as a pollutant in the United States.

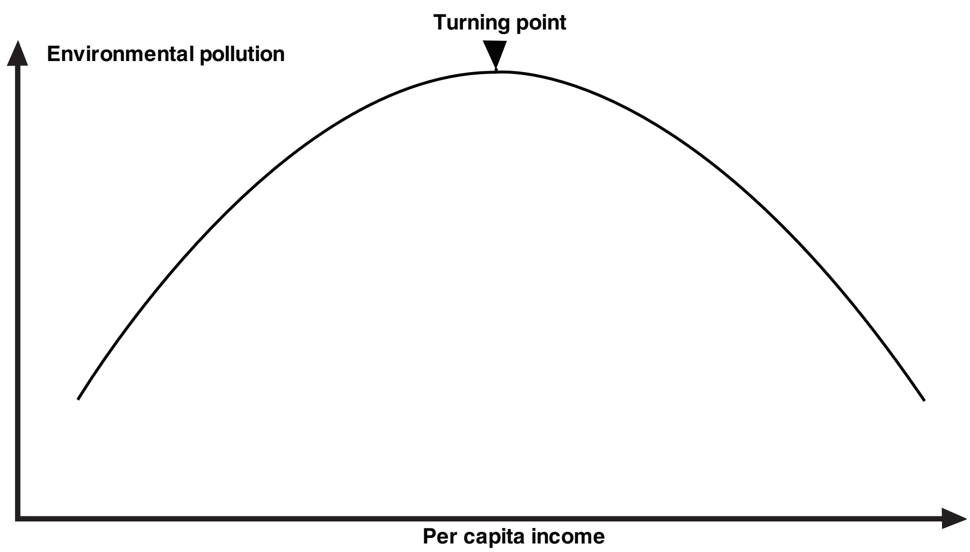
degradation. See appendix V for more information on the studies we reviewed.

Empirical Studies of the Relationship between Economic Growth and Environmental Quality Yield Mixed Results

The empirical studies we reviewed did not consistently find a relationship that showed pollution initially increasing as per capita income increases and then starting to decrease when income rises beyond a certain level. However, such a relationship was found more often for some types of pollutants than others.

If such a relationship between pollutants and economic growth is presented graphically, it would form an "inverted U curve," as shown in figure 11. The point where the curve changes from an upward slope—pollution increasing with income—to a downward slope is called the "turning point."

Figure 11: Hypothetical Inverted U-Shaped Curve, Showing Relationship Between Per Capita Income and Environmental Pollution



Source: GAO.

In conducting these studies, researchers typically used various measures of environmental quality, such as a specific pollutant or a composite measure of environmental quality.[32] In addition, to measure economic growth, the studies commonly used per capita income, and in most cases, the income levels were converted to 1985 U.S. dollars either by exchange rates or purchasing power parity rates.[33] The per capita income level for the United States for 1985 was $16,410 under both the exchange rate and purchasing power parity methods; for Japan, it was $10,900 for the former and $12,340 for the latter; for Mexico, $2,180 and $4,745; and for China, $280 and $785.

While overall the results of the studies are not consistent regarding an “inverted U curve” relationship between pollution and economic growth, they are more consistent in showing this relationship between pollutants with localized and near-term effects, such as sulfur dioxide and particulate matter. On the other hand, studies of substances with global and long-term effects, such as carbon dioxide, sometimes did not find a turning point or found a turning point beyond the income levels of the countries in the study.

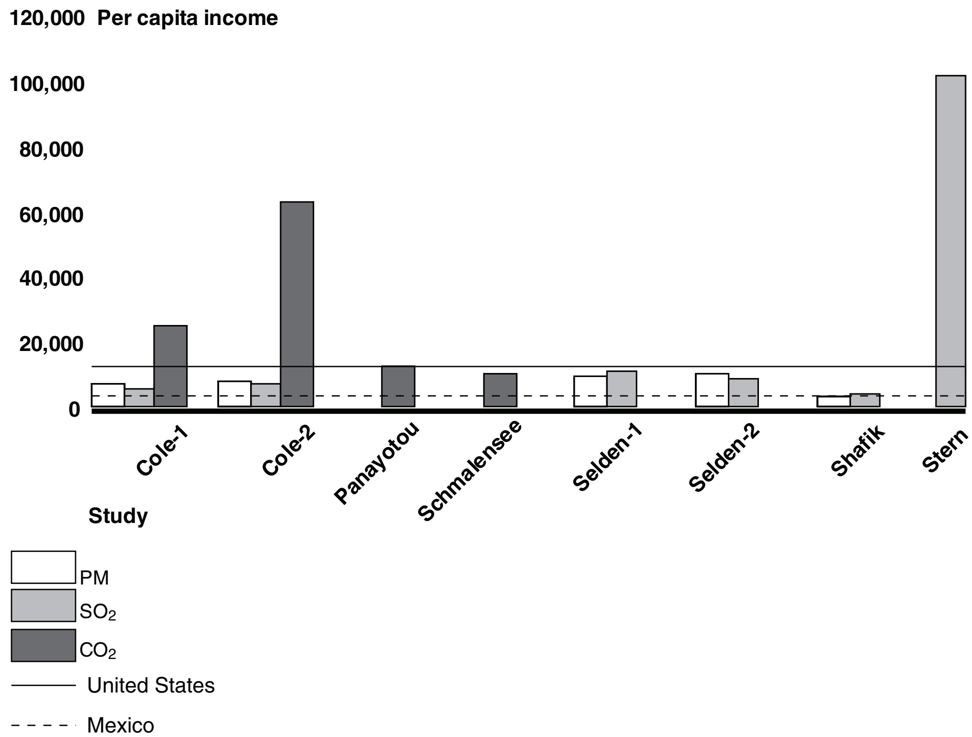
[32] The source for the environmental data most often used in these studies was the Global Environmental Monitoring System, compiled by the United Nations, except for data on carbon dioxide emissions from the U.S. Oak Ridge National Laboratory. Income data from different countries were often adjusted to comparable units in terms of exchange rates or purchasing power. In general, the data could be from as many as 149 economically developing and developed countries for 1960 through 2000 or any year during that period. Models differ in the exact specification of their equations, such as the number and type of other factors that are included in the model (e.g., international trade, population density) and the mathematical form of the relationship tested.

[33] To compare incomes across countries, incomes are converted to U.S. dollars in one of two ways: (1) using the official exchange rate between the dollar and the other currency or (2) using purchasing power parity rates—an international dollar that has the same purchasing power in another country as the dollar has in the United States.

For example, as shown in figure 12, the estimated turning point for sulfur dioxide in the studies we reviewed using the purchasing power parity method was typically in the range of $4,000 to $11,000.[34] While these estimated turning points were higher than per capita incomes in China and Mexico, they were generally below the per capita incomes in Japan and the United States in 1985. In addition, some estimated turning points for particulate matter were in the range of $3,000 to $10,000, which is less than per capita incomes in Japan, Mexico, and the United States. However, not all the studies we reviewed found a turning point for pollutants with localized effects. Specifically, one study found a turning point for sulfur dioxide at a per capita income level far higher than any country's level in 1985, and another study did not find a turning point for particulate matter. The studies of carbon dioxide we reviewed either estimated a turning point in the range of $10,000 to $63,000, which is above the per capita income level of most countries, except for a few developed countries, or found that there was no turning point (for example, because emissions and per capita incomes increased together).

[34] All numbers are presented in 1985 dollars converted by purchasing power parity.

Figure 12: Estimated Turning Points Found in Selected Studies of Particulate Matter, Sulfur Dioxide, and Carbon Dioxide



Source: GAO.

Note: Cole-1 and Cole–2 from Cole, Rayner, and Bates, "The Environmental Kuznets Curve: An Empirical Analysis," *Environment and Development Economics* (1997)—estimates from two models; Panayotou from Panayotou, Sachs, and Peterson, "Developing Countries and the Control of Climate Change: Empirical Evidence," Discussion Paper #45, Harvard Institute for International Development (1999); Schmalensee from Schmalensee, Stoker, and Judson, "World Carbon Dioxide Emissions: 1950-2050, "*Review of Economics & Statistics* (1998); Selden-1 and Selden-2 from Selden and Song, "Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions?," *Journal of Environmental Economics and Management* (1994)—two models estimated; Shafik from Shafik, "Economic Development and Environmental Quality: An Econometric Analysis," *Oxford Economic Papers* (1994); Stern from Stern and Common, "Is There an Environmental Kuznets Curve for Sulfur?," *Journal of Environmental Economics and Management* (2001).

Researchers suggested reasons an “inverted U” relationship is found more often for sulfur dioxide and particulates than for carbon dioxide. For example, they noted that the possible costs of climate change due to increased carbon dioxide emissions are borne globally and by future generations rather than locally and currently. Furthermore, the awareness of the problem of climate change is more recent than the awareness of the health effects associated with sulfur dioxide and particulates; policies to control carbon dioxide emissions were generally not in effect during the period of time analyzed by these studies.

Various Theoretical Explanations Have Been Suggested for the Relationship of Economic Growth and Environmental Quality

Other studies have sought to understand the factors underlying the relationship between economic growth and environmental quality. These studies generally agree that income is a proxy for a number of other factors that may be influencing environmental quality as countries develop economically. These factors include, for example, changes in a country’s economic structure, international trade, and a country’s preference for environmental quality. Nevertheless, researchers do not agree on the importance and role of any single factor. These three factors are discussed below.

- **Changes in a country’s economic structure.** Some studies pointed out that the relationship between economic growth and environmental quality reflects changes in an economy’s structure as economies develop and is not directly due to changes in income. Initially, these studies note, economies are primarily agrarian and produce little pollution. As these economies grow, the share of national output based on agriculture decreases, while the share based on more pollution-intensive manufacturing increases; hence pollution increases. At the later stages of development, the share of national output based on manufacturing decreases, while the share based on less pollution-intensive services increases; hence, pollution decreases.

- **The role of trade.** Other studies noted that international trade can affect patterns of production and environmental quality. That is, trade allows economically developed countries to emphasize cleaner types of industries and to rely on imports from less-developed countries for goods produced by more polluting industries. As a result, the improvement in some developed countries' environmental indicators is partly due to the contraction of their more polluting industries and the transfer of these industries to the less developed countries. However, researchers also observed that this process—and consequent improvement in environmental quality—cannot continue indefinitely because the relocation of polluting industries to other countries cannot continue indefinitely.[35]

- **Preference for environmental improvement.** According to still other studies, the relationship between economic growth and environmental quality reflects a country's preference for environmental improvement. That is, environmental improvement could be described as a "luxury good," that is, a good that people will seek more of as their incomes grow beyond subsistence level. Thus, in countries living at subsistence levels, pollution is accepted as a side effect of economic development, and people are not willing to reduce their consumption of basic necessities in order to set aside resources for environmental protection. However, as a country's economy grows and incomes increase, people become more willing to divert a portion of their resources from current consumption to improve the environment. This economic growth, in turn, leads to stronger support for environmental legislation and new regulations to protect the environment.

Studies have also discussed other factors—such as technology, population density, political environment, and environmental regulations—that may play key roles in shaping environmental quality as economies grow. Regardless of their views, researchers generally agree that better data and more detailed research are needed to conclusively identify the factors that either directly, or indirectly through per capita income, influence environmental quality.

[35] The empirical studies we reviewed that examined the role of trade on environmental quality did not provide support for the suggestion that exporting polluting industries (sometimes called "environmental dumping") accounts for the observed reduction in some pollutants in developed countries.

Conclusions

Of the three substances we reviewed, sulfur dioxide emissions have received the most attention in the countries we examined. All of these countries have undertaken at least some measures to reduce sulfur dioxide emissions. Past trends and projections in all countries seem to be affected by economic growth and health concerns. The economically developed countries began this process much earlier—as far back as the 1970s or 1980s—and they have been more successful thus far in realizing reductions than the three developing countries. In the developing countries, sulfur dioxide emissions declined (though in China and Mexico they have started to increase again), but they may decrease in the future if new policies are implemented and well enforced. While data on sulfur dioxide are far from complete, they are more readily available from country sources than data on the other two substances, particularly in developing countries. Since sulfate aerosol is a climate cooling agent, it is likely that reductions in sulfur dioxide emissions will result in some warming, at least at a regional level.

Black carbon is being addressed indirectly through measures designed to reduce particulate matter in all of the developed countries and to a lesser extent in the developing countries. Emissions have begun to decline in developed countries, with the exception of Japan, according to the database we used, largely as a result of regulations limiting diesel fuel emissions, the major source of developed countries' black carbon. Developing countries have not seen comparable declines in black carbon emissions, because home heating and cooking largely rely on burning coal and wood. Because small coal- or wood-burning stoves are widely used in these countries, black carbon emissions are more widely dispersed than, for example, sulfur dioxide emissions, which are usually associated with large power plants. Consequently, developing countries may find it challenging to control emissions of black carbon, at least for the foreseeable future. In addition, forest burning and land-clearing, major sources of black carbon emissions, are more prevalent in developing countries. Reliable measurements of black carbon from all seven countries are sparse.

Tropospheric ozone levels are difficult to reduce because they result from emissions of precursor substances produced by a very diverse range of sources. Nevertheless, developed countries have had some success over the past decade in reducing high ozone levels, particularly in major urban and suburban areas. This trend is likely to continue over the next two decades, but ozone concentrations in developing countries may continue to rise along with industrialization for the foreseeable future. The developing countries we analyzed are only starting to take measures to reduce ozone and its precursor substances. Consequently, ozone levels in the free troposphere are likely to increase globally as a result of a net increase in emissions of its precursors at the surface. Methane is expected to play a particularly important role in the formation of ozone in the future.

The results of economic research do not convincingly establish whether a country's environmental pollution initially increases and then, with economic growth, decreases. This type of relationship seems to apply to some types of pollutants but not to others. Researchers generally agree, however, that unless the incentives facing producers and consumers change with higher incomes, pollution will continue to increase as economies grow. In other words, income growth, while a necessary condition, is not sufficient to reverse environmental degradation. Environmental policies must follow to induce appropriate responses and turn the pollution path around.

Agency Comments

We provided a draft of this report to the Secretary of Energy and the Administrator of EPA for review and comment. The agencies provided written clarifying comments, which we incorporated where appropriate.

As arranged with your offices, we plan no further distribution of this report for 30 days after the date of this letter, unless you publicly announce its contents earlier. At that time, we will send copies of this report to the Ranking Minority Members of the Committee on Energy and Commerce, House of Representatives, and its Subcommittees on Energy and Air Quality and Oversight and Investigations; the Secretary of Energy; the Administrators of the Environmental Protection Agency, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration; the Director, National Science Foundation; the Director, Climate Change Science Program Office; and other interested parties. We will make copies available to others upon request. In addition, copies of this report are available at no cost at our Web site, www.gao.gov.

If you have any questions about this report, please contact me at (202) 512-3841. Key contributors to this report are listed in appendix VI.

John B. Stephenson
Director, Natural Resources
and Environment

Scope and Methodology

To obtain information on recent research relating to the climate change characteristics of the three substances, we contacted scientists in four federal agencies: the Department of Commerce's National Oceanic and Atmospheric Administration; the Department of Energy; the National Aeronautics and Space Administration; and the National Science Foundation. These scientists were recommended by staff at the U.S. Climate Change Science Program, an interagency research coordinating body.

In analyzing trends for the three pollutants, we found that the availability and quality of data varied considerably, especially in developing countries. Except for countries that are members of the EU or participate in the CLRTAP, governments are not required to report their emissions of these substances internationally.[1] We found no standardized system for calculating and reporting emissions. Moreover, some of the data reported here are based on direct measurements, while others are estimated using proxy data (such as fuel use information), which may be less exact than measured data. Most of the data used in this study, except where noted, are taken from government sources. Dr. Tami Bond of the National Center for Atmospheric Research; Dr. Loretta Mickley of Harvard University; Dr. Michael Prather of the University of California, Irvine; and Dr. David Streets of Argonne National Laboratory provided comments and insights on certain sections of the report. The information on foreign countries' emissions levels and legislation does not reflect our independent analysis.

To obtain information on policies and measures, we first sought a comprehensive source of information for each country. Because we found no such source, we contacted government, academic, and other researchers and analysts in the United States and the other countries, and the countries' embassies in the United States. We also gathered information from government publications, web sites, e-mail correspondence with U.S. and foreign government officials, and discussions with embassy personnel. While we tried to make this report as complete as possible, there may be additional policies and programs underway that are not addressed here.

[1] Under the Framework Convention on Climate Change, developed (Annex I) countries generally report their emissions of sulfur dioxide along with their emissions of the six conventional greenhouse gases. This is the source of our data on Japanese sulfur dioxide emissions.

To assess the literature on the relationship between economic growth and environmental pollution, we conducted computerized literature searches to identify relevant articles. To help us determine which articles to focus on, we sought guidance from recognized experts who specialize in this field. The extent of governmental action to control a specific pollutant is believed to be one important factor—but not the only factor—in explaining the relationship between economic growth and emissions of that pollutant. Therefore, even though few countries have acted to control carbon dioxide emissions and have done so recently, we included studies that examined the relationship between economic growth and such emissions.

We conducted our review between October 2001 and April 2003 in accordance with generally accepted government auditing standards.

Programs and Measures to Reduce Emissions of Sulfur Dioxide

Country	Measures
United States	Section 109 of the Clean Air Act requires EPA to establish National Ambient Air Quality Standards (NAAQS) for air pollutants that may endanger public health and welfare. EPA established such NAAQS for sulfur dioxide. Under the 1990 amendments, areas not in attainment with the NAAQS must meet special compliance schedules.
	Section 110 of the Clean Air Act requires states to adopt plans, known as State Implementation Plans (SIP), which detail the regulations a state will use to implement, maintain, and enforce the NAAQS. EPA must approve each SIP, and if a SIP is not acceptable, EPA may take over enforcement of the Clean Air Act in that state.
	Section 111 of the Clean Air Act requires EPA to establish nationally uniform, technology-based standards called New Source Performance Standards for categories of new industrial facilities, such as power plants, steel mills, and smelters. These standards limit the amount of certain pollutants, including sulfur dioxide, that may be emitted.
	Sections 160-169 of the Clean Air Act establish requirements for the prevention of significant deterioration (PSD) of air quality in areas that have attained the NAAQS. The act divides clean air areas into three classes and specifies the increments of sulfur dioxide and particulate matter pollution allowed in each. In order to receive a PSD permit, a new or modified major source of pollution must show that it will not contribute to a violation of the increments or of the national ambient air quality standards and that it will use best available control technology (BACT). This provision is referred to as PSD New Source Review.
	Sections 171-173 of the Clean Air Act establish pre-construction permitting requirements for major new and modified sources in non-attainment areas (areas that have not attained the NAAQS). To receive a permit, such sources must, among other things, (1) obtain emissions offsets, thereby assuring that reasonable progress toward attainment of the NAAQS will occur, and (2) comply with the "lowest achievable emissions rate."
	Title IV of the Clean Air Act created EPA's Acid Rain Program, which caps sulfur dioxide emissions from virtually all U.S. electric power plants at 8.95 million tons. Plant operators were required to reduce their emissions through any combination of strategies, including installing scrubbers, switching to natural gas or low-sulfur coal, or trading emissions allowances. The first phase of the program ran from 1995 to 1999, and the second phase, with more stringent caps, began in 2000 and will run indefinitely. The program features a provision that allows power plants that exceed their emissions targets to "bank" extra allowances during the first phase of the program and then use these banked allowances during the more stringent second phase.
United Kingdom	The United Kingdom's 1956 and 1968 Clean Air Acts, among other things: • authorized local councils to set up smokeless zones and make grants to householders to convert their homes from traditional coal fires to heaters fueled by gas, oil, smokeless coal, or electricity. • set limits on sulfur dioxide emissions from small power plants. • The United Kingdom's Environment Act of 1995 requires the government to produce a national air quality strategy that identifies clear, measurable targets for improved air quality in the United Kingdom. This strategy is to be developed based on understanding of the health effects of the pollutants concerned and costs of emission reduction methods and aims to improve air quality by 2005. The strategy sets standards and objectives for sulfur dioxide and seven other air pollutants. The 1995 act also established a system of local air quality management, under which authorities are required to assess the current and future quality of air in their areas against the national air quality strategy objectives.

(Continued From Previous Page)

Country	Measures
	The Convention on Long-Range Transboundary Air Pollution (CLRTAP) binds the United Kingdom to reduce sulfur, as do certain CLRTAP protocols: • The 1994 Oslo Protocol on Further Reduction of Sulfur Emissions, which aims at gradually achieving critical loads of sulfur. • The 1999 Gothenburg Protocol, signed but not ratified by the United Kingdom, which set emissions ceilings for 2010 for sulfur dioxide and three other pollutants, is expected to enter into force as early as 2003. (CLRTAP covers more European countries than the EU, but the EU directives generally require more ambitious emissions reductions than the CLRTAP protocol.)
	EU directives which require the United Kingdom to reduce sulfur dioxide emissions include: • The First Daughter Directive (1999/30/EC), under which EU members must establish, and achieve by 2005, a legally binding limit on concentrations of sulfur dioxide and three other substances. • The Directive on the Incineration of Wastes (2000/76/EC), which sets limits on emissions of sulfur dioxide and other substances from waste incineration plants. • The Large Combustion Plant Directive (2001/80/EC), which sets limits on sulfur dioxide and nitrogen oxides from combustion plants with a thermal input of 50 megawatts or greater.
Germany	• The Large Combustion Ordinance contains emissions ceilings for new power plants in Germany. • The CLRTAP requirements and EU directives also apply to Germany.
China	The Air Pollution Control Law, enacted in 1987 and amended in 2000, aims to improve air quality in key urban areas. Specifically, it • broadens the scope of affected industries beyond industrial sources and power plants, to include automobiles, ships, domestic heating, and cooking stoves; • provides an incentive for using high-quality, low-sulfur coal and renewable energy; • allows so-called “priority cities” to designate zones within which all burning of high-polluting fuel (i.e., coal) can be prohibited and calls for the phase-out of a form of dirty coal in large- and medium-sized cities; • requires new or expanded sulfur dioxide-emitting power plants or large- and medium-sized industrial enterprises to install desulfurization equipment; and • encourages cities to replace individual household coal heating stoves with centralized district heat.
	The Energy Conservation Law, which entered into force in January 1998, promotes energy conservation and efficiency. Other energy conservation laws also exist.
	A fuel tax has been imposed on high-sulfur coals, and between January and September 2000, 4,732 mines producing high-sulfur coal were closed.
	Subsidies for coal have been greatly reduced since 1984.

Source: GAO.

Programs and Measures to Reduce Emissions of Black Carbon or Particulate Matter

Country	Measures
United States	The Heavy Duty Diesel Rule, promulgated in 2001, will require significant future reductions in highway diesel engine particulate matter emissions. It will also require diesel oil refiners to reduce most sulfur from diesel fuel by 2006 in preparation for new engines in 2007. In 2030, when the rule is fully implemented, it is expected that particulate matter from diesel vehicles will be reduced by 130,000-140,000 tons per year relative to 1996.
United Kingdom	The Smoke Control Act of 1993 empowers local authorities to declare a smoke control area if it appears that air quality standards will not be met. Under the law, the local government can require that only certain fuels be used for domestic heating.
	EU directives aimed at reducing particulate matter include: • Directive 1998/70/EC, which sets the maximum allowable sulfur content of gasoline and diesel fuel. • The First Daughter Directive (1999/30/EC), which contains a particulate matter standard for the EU countries. • The Directive on the Sulfur Content of Certain Liquid Fuels (1999/32/EC), which mandates reductions in sulfur content of diesel fuel to enhance performance of emissions-reduction devices. • Directive 1999/96/EC, which sets the emission limit values and implementation dates in two stages for heavy duty vehicles (Euro III and IV). The standards cover emissions of particulate matter and ozone precursors.
Germany	The EU directives described above also apply to Germany.
China	Euro I and II standards for the control of emissions from diesel vehicles.
India	Euro I and II standards for the control of emissions from diesel vehicles.

Source: GAO.

Programs and Measures to Reduce Ground-Level Ozone

Country	Measures
United States	The Clean Air Act has resulted in the creation of several trading programs for reducing nitrogen oxide emissions in the electric utility sector: • EPA's Acid Rain Program sets emissions rates for all affected utilities. Unlike sulfur dioxide, there is no cap on total nitrogen oxide emissions, but utilities may choose to over-control at units where it is easier to do so and average these emissions with those at their other units, thereby achieving overall emissions reductions at lower costs. • The EPA Nitrogen Oxides SIP Call[a] requires 19 states and the District of Columbia to reduce total nitrogen oxide emissions from utilities by a certain number of tons each year; compliance for Phase I must be achieved no later than May 31, 2004. Power producers subject to these regulations are allowed to trade emissions allowances to meet the required limits. • The Nitrogen Oxides Budget Trading Program, begun in 1999 in nine Northeastern states, aims to reduce nitrogen oxide emissions during the summer months to enable states to attain the standard for ground-level ozone. Like the programs above, it is a cap and trade program, under which total emissions are capped, and affected parties may trade emissions allowances.
	The Clean Air Act has also provided the framework for ozone-reducing reductions in the transportation sector. The most recent regulation with significant impact on transportation sector ozone precursors is the Tier 2 program, which was promulgated in 2000 and will be phased in starting in 2004, when refiners must produce low-sulfur fuel for passenger vehicle gasoline. Tier 2 also sets tailpipe emission standards for all classes of passenger vehicles, including sport utility vehicles and light-duty trucks.
	A Clean Air Act regulation requires the combustion of methane and other non-methane organic compounds from large landfills. The regulation also contains a performance standard based on the allowable concentration of methane measured at the landfill. In addition to programs regulating emissions from cars and trucks, EPA regulates emissions of nitrogen oxides and hydrocarbons from aircraft, ships, locomotives, recreational vehicles, off-road diesel equipment (e.g., farm and construction equipment), and spark-ignition engines, such as chain saws, lawn mowers, and forklifts.
	The U.S. Department of Transportation administers a program called "Congestion Mitigation and Air Quality Improvement" aimed at reducing ozone and its precursors (as well as particulate matter) by funding new transit services, bicycle, and pedestrian improvement, alternative fuel projects, traffic-flow improvements, and other emissions-reducing projects.
	In the industrial sector, the Clean Air Act specifies performance standards for new industrial sources. The standards, called New Source Performance Standards, establish maximum emission levels for new or modified major stationary sources, such as steel mills and smelters. These standards also apply to power plants.
United Kingdom	CLRTAP Protocols that bind the United Kingdom and other European countries include: • The 1988 Sofia Protocol, which set a target for emissions of nitrogen oxides. • The 1991 Geneva Protocol, which requires a reduction in emissions of volatile organic compounds. • The 1999 Gothenburg Protocol, signed but not ratified by the United Kingdom, which sets emissions ceilings for nitrogen oxides, volatile organic compounds, and two other substances.

Country	Measures
	The EU directives aimed at reducing ozone and/or its precursors include: • Directives on Air Pollution by Ozone (92/72/EC and 2002/3/EC), which establish thresholds for ozone and require that threshold exceedances must be reported to the EU Commission and to the public. • The Directive on VOC Emissions from the Storage of Petrol (94/63/EC), which sets guidelines for reducing volatile organic compound emissions from the storage and distribution of petrol (gasoline) from terminals to service stations. • The Framework Directive (96/62/EC), which established the framework under which the EU countries would agree on emissions limits for certain pollutants. The Directive requires that, if limits are exceeded, member states devise abatement programs to reach the limits within a set deadline. • The Directive 98/69/EC, which establishes emission limit values and implementation dates in two stages for light-duty vehicles (Euro III and IV). The standards cover ozone precursors and particulate matter. • The First Daughter Directive (99/30/EC), which sets limit values for nitrogen oxides (and other substances.) • The VOC Solvents Directive (99/13/EC), which limits emissions of volatile organic compounds. • The Directive on Landfills (99/31/EC), which aims to harmonize controls on the landfill of waste throughout the EU. Its main focus is on common standards for the design, operation and aftercare of landfill sites. It also aims to reduce the amount of methane emitted from landfill sites. • The Large Combustion Plant Directive (2001/80/EC), which sets limits on sulfur dioxide and nitrogen oxides from combustion plants with a thermal input of 50 megawatts or greater.
	The National Emission Ceiling Directive (2001/81/EC), which sets ceilings for emissions of nitrogen oxides, sulfur dioxide, ammonia, and volatile organic compounds to be attained by 2010. (As of early 2003, this protocol was not yet in force.)
Germany	The CLRTAP requirements and EU directives cited above apply to Germany.
Japan	The Air Pollution Control Law requires stations in several parts of the country to monitor for nitrogen dioxide, suspended particulate matter, sulfur dioxide, carbon monoxide, and photochemical oxidants. It also establishes maximum permissible limits on exhaust gases from motor vehicles.
	The Automobile Nitrogen Oxides Law sets the fundamental policies and plans for reducing the total volume of nitrogen oxides for specific automobiles.
China	Although the government does not require the reporting of data on ozone concentrations, the city of Beijing does so when ozone levels become particularly high.
	Euro I and II standards for the control of motor vehicle emissions, including carbon monoxide, hydrocarbons, and nitrogen oxides.
Mexico	Mexico's Tag Zero Program offers a 2-year exemption from Mexico City's "car-free" policy for drivers of clean cars. Under the program, drivers of new cars or cars that have been upgraded with catalytic converters may drive in the city any day of the week, while owners of cars without such certification may drive on only a certain number of days per week. (An exempted, or clean, car is denoted by a zero on a sticker placed on the back window of the car. The car's license plate indicates the days a car may not be driven if it does not have a sticker.) The Tag Zero program thus rewards the purchase of clean vehicles.
India	Euro I and II standards for the control of motor vehicle emissions, including carbon monoxide, hydrocarbons, and nitrogen oxides.

Source: GAO.

[a]The Nitrogen Oxides SIP Call is authorized under section 110 of the Clean Air Act. A SIP is a State Implementation Plan, which is a proposal submitted by each state to EPA containing emission limitations and other control measures to attain, maintain, and enforce the NAAQS. EPA may issue a SIP Call under the act when it finds that the applicable SIP fails to comply with a requirement of the act. The SIP Call requires the state to revise its SIP.

Summary of Results of Selected Studies on Economic Growth and Environmental Pollution

The following table presents information on the studies of economic growth and environmental quality that we reviewed.

Table 2: Results of Selected Studies of Economic Growth and Environmental Quality

Study's author(s) and year	Estimated per capita income for turning points, by type of emission[a]		
	Particulate matter	Sulfur dioxide	Carbon dioxide
Based on exchange rates			
Grossman and Krueger, "Economic Growth and Environment," *Quarterly Journal of Economics* (1995)	None found[b]	$4,100	Not studied
Holtz-Eakin and Selden, "Stoking the Fires? CO_2 Emissions and Economic Growth," *Journal of Public Economics* (1995)	Not studied	Not studied	$35,400[c]
Panayotou, "Demystifying the Environmental Kuznets Curve: Turning a Black Box into a Policy Tool," *Environment and Development Economics* (1997)	Not studied	5,000	Not studied
Roberts and Grimes, "Carbon Intensity and Economic Development 1962-91: A Brief Exploration of the Environmental Kuznets Curve," *World Development* (1997)	Not studied	Not studied	None found
Based on purchasing power parity			
Shafik, "Economic Development and Environmental Quality: An Econometric Analysis," *Oxford Economic Papers* (1994)	$3,300	3,700	Not studied
Selden and Song, "Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions?," *Journal of Environmental Economics and Management* (1994)—two models estimated	9,600 9,800	10,700 8,900	Not studied
Cole, Rayner, and Bates, "The Environmental Kuznets Curve: An Empirical Analysis," *Environment and Development Economics* (1997)—two models estimated	7,300 8,100	5,700 6,900	25,100 62,700
Schmalensee, Stoker, and Judson, "World Carbon Dioxide Emissions: 1950-2050," *Review of Economics & Statistics* (1998)	Not studied	Not studied	10,000
Unruh and Moomaw, "An Alternative Analysis of Apparent EKC-type Transitions," *Ecological Economics* (1998)	Not studied	Not studied	None found
Panayotou, Sachs, and Peterson, "Developing Countries and the Control of Climate Change: Empirical Evidence," Discussion Papers #45, Harvard Institute for International Development (1999)	Not studied	Not studied	12,000
Stern and Common, "Is There an Environmental Kuznets Curve for Sulfur?" *Journal of Environmental Economics and Management* (2001)	Not studied	101,200[d]	Not studied

Source: GAO.

[a]All numbers are in 1985 dollars unless otherwise noted.

[b]Grossman and Krueger estimated a turning point separately for heavy particulate and smoke. While no turning point for heavy particulate was found, the turning point for smoke was $6,200.

[c]In 1986 dollars.

[d]In 1990 dollars.

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