

Climate Change and Air Quality

By Anne Grambsch

Introduction

Air pollution is a major concern in the U.S.: it can threaten human health, damage ecosystems, cause haze and reduce well-being. At the same time, the Earth's climate system has the potential to both affect, and be affected by, air pollution. The first section of this paper is intended to provide background on the current status and trends of air pollutant emissions and concentrations, with a focus on mobile sources. The next section briefly describes historical and ongoing programs to reduce mobile source emissions. The third section discusses the potential interactions between climate, climate change and air quality. The last section details a few key research needs to further our understanding of these interactions.

Current Status and Trends¹

Over the past 30 years, there have been substantial reductions in air pollutant emissions and concentrations despite large increases in total U.S. population, vehicle miles traveled (VMT), energy consumption, and gross domestic product (GDP). Since 1970 total U.S. population increased 36%, VMT increased 143%, energy consumption increased 45% and GDP increased 158% while aggregate criteria air pollutant emissions decreased 29% (see Figure 1). Changes in individual pollutants range from a 98% decrease in lead (Pb) emissions to a 20% increase in nitrogen oxides (NO_x) emissions.

To protect public health and welfare, EPA has established National Ambient Air Quality Standards (NAAQS), for six criteria pollutants: carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO₂), ozone (O₃), particulate matter (PM), and sulfur dioxide (SO₂). EPA tracks trends of these pollutants in terms of both ambient air concentrations, using actual measurements of pollutant concentrations at monitoring sites, and emissions, which are based on monitored readings and engineering calculations. Table 1 shows that air quality, based on concentrations of criteria air pollutants, has improved nationally over the last 20 years. Total emissions, with the exception of nitrogen oxides, have also declined.

These improvements are a result of effective implementation of clean air laws and regulations, as well as improvements in the efficiency of industrial technologies. Despite great progress in air quality improvement, the ambient air quality in many areas still falls short of the NAAQS. In 2000, approximately 121 million people lived in counties with air quality that did not meet EPA's health-based standards for at least one criteria air pollutant. Nonetheless, the declining trends in the emissions and monitored concentrations of several criteria pollutants provide strong evidence that air quality in the U.S. has significantly improved over the past 30 years.

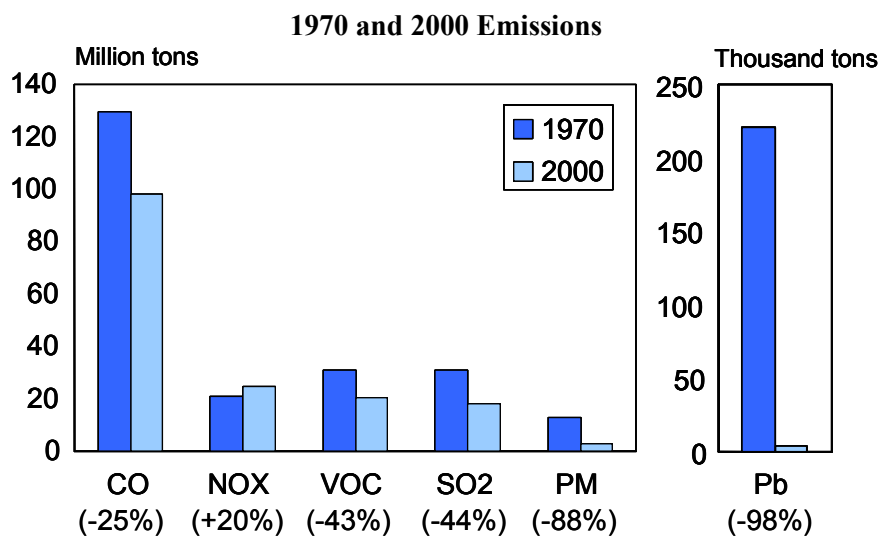


Figure 1. The chart compares 1970 and 2000 air pollutant emissions. Emissions decreased for CO, VOC, SO₂, PM, and Pb. Only NO_x emissions increased in that period. Source: USEPA, 2001b.

Table 1. Percent change in air quality and emissions: 1980-1999. Source: USEPA, 2001a.

Pollutant	Percent Change in Air Quality (Pollutant Concentrations)		Percent Change in Emissions	
	1980-1999	1990-1999	1980-1999	1990-1999
Nitrogen Dioxide	-25	-10	+4	+5
Ozone/VOC*				
# 1-hour	-20	-4	-31	-14
# 8-hour	-12	No Change		
Sulfur Dioxide	-50	-36	-27	-20
Particulate Matter ₁₀ **	---	-18	---	-15
Particulate Matter _{2.5} **	Trend data not available		---	-17
Carbon Monoxide	-57	-36	-21	-2
Lead	-94	-60	-94	-16

* Ozone and many particles are not emitted directly into the air. They are formed after directly emitted gases, such as volatile organic compounds (VOCs), react chemically to form them.

** Includes only directly emitted particles.

Note: Negative numbers indicate improvements in air quality or reductions in emissions. Positive numbers show where emissions have increased.

Note: Air quality concentrations do not always track nationwide emissions. For example, most monitors are located in urban areas so air quality is most likely to track changes in urban air emissions rather than in total emissions. In this case, the 20-year decline in ambient NO₂ levels closely tracks the 19-percent reduction in emissions from gasoline-powered vehicles over the same time period. In addition, nitrogen chemistry in the atmosphere is nonlinear and, therefore, a change in NO_x emissions may not have a proportional change in ambient concentrations of NO₂. The relationship between emissions and ambient air quality levels is dependent on a number of factors such as concentrations of compounds, which react with NO_x emissions (e.g., free radicals and VOCs), as well as the form and concentration of various nitrogen compounds in the area being monitored.

Mobile Sources

Air pollution in the United States comes from many types of engines, industries, and commercial operations. These include: stationary sources, such as factories, power plants, and smelters; smaller sources, such as dry cleaners and degreasing operations; mobile sources; and natural sources, such as windblown dust and wildfires. The focus of this paper is on mobile sources, which pollute the air through combustion processes and fuel evaporation. In addition, travel on roads results in “fugitive dust” emissions (dust generated from road travel is called fugitive because it does not enter the atmosphere in a confined flow stream). These emissions contribute to air pollution nationwide and are the primary cause of air pollution in many urban areas.

Mobile sources refer to a wide variety of vehicles, engines, and equipment that move, or can be moved, from place to place. On-road (or highway) sources include vehicles used on roads for transportation of passengers or freight (e.g., cars, trucks and buses). Non-road (or off-road) sources include vehicles, engines, and equipment used for construction, agriculture, transportation, recreation, and many other purposes (e.g., dirt bikes, snowmobiles, tractors, marine engines, aircraft, locomotives). Within these two broad categories, size, weight, use, and horsepower further distinguish on-road and non-road sources.

Mobile sources make up a significant portion of emissions of four air pollutants: CO, NO_x, volatile organic compounds (VOCs), and PM. These are described in more detail below. Mobile sources also produce several other important air pollutants, such as air toxics and greenhouse gases.

Carbon Monoxide

Transportation accounted for 77% of the nation’s total CO emissions in 1999. Despite a 57% increase in vehicle miles traveled (VMT), emissions from on-road vehicles decreased 56% during the past 20 years as a result of automotive emissions control programs. However,

emissions from all transportation sources have decreased only 23% over the same period, primarily due to a 42% increase in off-road emissions, which has offset the gains realized in reductions of on-road vehicle emissions.

Table 2. 1999 carbon monoxide emissions (in thousand short tons).

Total emissions	97,441
Transportation	75,151
On-road	49,989
Non-road	25,162

Nitrogen Oxides

Nitrogen oxides (NO_x) play a major role in the formation of ozone in the atmosphere through a complex series of reactions with volatile organic compounds (VOCs). Anthropogenic emissions of NO_x account for a large majority of all nitrogen inputs to the environment. The major sources of anthropogenic NO_x emissions are high-temperature combustion processes, such as those occurring in automobiles and power plants. Transportation accounted for 56% of U.S. NO_x emissions in 1999. Emissions from transportation sources increased 16% overall for the period 1980 to 1999. While on-road emissions were virtually unchanged from 1980 levels, emissions from non-road sources increased 56%.

Table 3. 1999 nitrogen oxide emissions (in thousand short tons).

Total emissions	25,393
Transportation	14,105
On-road	8,590
Non-road	5,515

Over the past 10 years (1990-1999), NO_x emissions for both light duty gasoline vehicles and light duty gasoline trucks peaked in 1994 and then began a steady decrease (8% and 24% respectively) through 1999, for an overall increase of 19%. The decrease after 1994 can be attributed primarily to the implementation of the Tier 1 emission standards, which lowered NO_x emissions from new cars and light duty trucks. In contrast, NO_x emissions from heavy duty vehicles, both gasoline and diesel, increased significantly from 1990 to 1999 (50% for gasoline and 61% for diesel). A portion of this increase is due to the increase in VMT for these categories (104% for heavy duty gasoline vehicles and 99% for heavy duty diesel trucks). Emissions from off-road vehicles, particularly diesel-fueled vehicles, increased steadily over the last 10 years (15% increase).

Ozone/VOC

Ground-level ozone continues to be a pollution problem throughout many areas of the United States. Ozone is not emitted directly into the air but is formed by the reaction of VOCs and NO_x in the presence of heat and sunlight. Ground-level ozone forms readily in the atmosphere, usually during hot summer weather. A variety of sources, including motor vehicles, emit VOCs. Nationally, transportation sources accounted for 47% of anthropogenic VOC emissions in 1999.

Table 4. 1999 volatile organic compound emissions (in thousand short tons).

Total emissions	18,145
Transportation	8,529
On-road	5,297
Non-road	3,232

VOC emissions from transportation decreased 24% over the past 20 years. On-road emissions decreased 41% from 1980 to 1999 but were partially offset by the 40% increase in non-road emissions. Recent control measures to reduce transportation sector emissions include regulations to lower fuel volatility and to reduce NO_x and VOC emissions from tailpipes. The effectiveness of these control measures is reflected in a decrease in VOC emissions from highway vehicles. VOC emissions from highway vehicles declined 18% since 1990, while highway vehicle NO_x emissions have increased 19% over the same period.

Particulate Matter

Particulate matter (PM) is the general term used for a mixture of solid particles and liquid droplets found in the air. The chemical composition and physical properties of these particles vary widely. Particles less than or equal to 2.5 micrometers in diameter, or PM_{2.5}, are known as “fine” particles. Those larger than 2.5 micrometers but less than or equal to 10 micrometers are known as “coarse” particles. PM₁₀ refers to all particles less than or equal to 10 micrometers in diameter. Fine particles result from fuel combustion (from motor vehicles, power generation, industrial processes), residential fireplaces and wood stoves. Fine particles also can be formed in the atmosphere from gases such as sulfur dioxide, nitrogen oxides, and volatile organic compounds. Coarse particles are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, crushing and grinding operations, and windblown dust.

Table 5. 1999 particulate matter (in thousand short tons).

	PM ₁₀
Total emissions	23,679
Non-traditionally inventoried, Total	20,634
- Unpaved roads	9,360
- Paved roads	2,728
- Misc./natural	8,546
Traditionally inventoried, total	3,045
- Transportation	753
- On-road	295
- Non-road	458

In 1999, transportation accounted for 25% of direct PM₁₀ emissions (coarse particles) from traditionally inventoried sources such as fuel combustion, industrial processes, and transportation). However, these traditionally inventoried sources made up only a small share, about 13%, of total direct PM₁₀ emissions. For direct PM_{2.5} emissions (fine particles) transportation accounted for about 28% of traditionally inventoried sources, which in turn made up 34% of all PM_{2.5} emissions nationwide. While miscellaneous and natural sources actually account for a large percentage of the total direct PM₁₀ and PM_{2.5} emissions nationwide, they can be relatively difficult to quantify compared to the traditionally inventoried sources.

Other Emissions

Lead. Twenty-five years ago, automotive sources were the major contributor of lead emissions to the atmosphere. The large reduction in ambient concentrations and emissions from 1980 to 1990 can be largely attributed to the phasing out of leaded gasoline for automobiles. Overall, lead emissions decreased 94% between 1980 and 1999. The 4% increase in lead emissions from 1998 –1999 is largely attributable to increased use of aviation gasoline.

Aviation gasoline is not regulated for lead content and can use significant amounts of lead to comply with octane requirements for aviation fuel.

Air Toxics. Hazardous air pollutants (HAPS), commonly referred to as air toxics, are pollutants known to cause, or suspected of causing, cancer or other serious human health effects or ecosystem damage. EPA is required to reduce air emissions of 188 air toxics listed in the Clean Air Act. The National Toxics Inventory 1996 emission estimates for the 188 HAPS totaled 4.6 million tons, with on-road sources accounting for 30% and non-road sources accounting for 20% of the total. Based on the data in the National Toxics Inventory, estimates of nationwide air toxics emissions have dropped approximately 23% between the baseline period (1990—1993) and 1996. Mobile sources contribute a large share (i.e., more the 40%) of emissions for several air toxics including benzene, 1,3-butadiene, acetaldehyde, acrolein, formaldehyde, and diesel particulate matter. EPA has identified 21 Mobile Source Air Toxics (MSATs), including several VOCs, as well as diesel particulate matter plus diesel emission organic gases (DPM+DEOG).

Greenhouse Gases. Transportation accounted for 1,877 teragrams of CO₂ equivalent² (Tg CO₂ Eq) in 2000, or about 27% of total U.S. greenhouse gas emissions (USEPA, 2002). Focusing on CO₂ emissions from fossil fuel combustion (excluding international bunker fuels³) the transportation sector accounted for the largest share – approximately 32% – of CO₂ emissions. Petroleum-based products supplied almost all of the energy consumed in transportation activities, with nearly two-thirds related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. Carbon dioxide emissions from fossil fuel combustion for transportation increased by 22% from 1990 to 2000 to 1,792 Tg CO₂ Eq. The growth in transportation sector emissions has been relatively steady, including a 3.5% single year increase in 2000.

Mobile Source Pollution Control Programs

Starting in the early 1970s, EPA set national standards that considerably reduced emissions of CO and other pollutants from motor vehicles. Today's cars, for example, typically emit 70 to 90% less pollution over their lifetimes than their 1970 counterparts (USEPA, 1994). Under the

Clean Air Act and subsequent Amendments in 1977 and 1990, tailpipe standards for cars were set and later tightened, emission standards for diesel-powered trucks and buses were adopted, and Inspection and Maintenance (I/M) programs were established and subsequently expanded to include more areas and allow for more stringent tests (see Table 6).

Table 6. Milestones in motor vehicle emissions controls.

1970	New Clean Air Act sets auto emissions standards.	1990	Clean Air Act Amendments set new tailpipe standards.
1974	EPA sets fuel economy standards.	1992	Oxyfuel introduced in cities with high CO levels.
1975	First catalytic converters are used for hydrocarbons and CO. First use of unleaded gas in catalyst equipped cars.	1993	Limits set on sulfur content of diesel fuel.
1981	3-way catalysts with on-board computers and O2 sensors appear.	1994	Phase-in of new vehicle standards and technologies begins.
1983	I/M programs are established in 64 cities.	1995	On-board diagnostic systems in 1996 model year cars. Phase I Federal Reformulated Gasoline sales begin in worst ozone nonattainment areas.
1989	Fuel volatility limits are set for RVP.	1998	Sales of 1999 model year California emissions equipped vehicles begin in the Northeast.

The 1990 Amendments to the Clean Air Act also introduced several new approaches to reducing motor vehicle-related air pollution. Fuel is considered along with vehicle technology as a potential source of emission reductions. And more attention is focused on reducing the growth in vehicle travel. The new provisions include:

- *Emphasis on Fuels:* The Clean Air Act mandates that improved gasoline formulations be sold in some polluted cities to reduce emissions of ozone-forming hydrocarbons and air toxics. Other programs set low vehicle emission standards to stimulate the introduction of even cleaner cars and fuels. EPA also regulates the vapor pressure of all gasoline during the summer months.

EPA has regulated highway diesel fuel quality since 1993 and most recently established low sulfur requirements in diesel fuel starting in 2006.

- *Non-road Engines:* The 1990 Clean Air Act requires EPA to consider emissions from off-highway vehicles as well as from highway vehicles such as cars and trucks.
- *Clean Transportation Alternatives:* The law requires the smoggiest cities to limit growth in vehicle travel by encouraging alternatives to solo driving.

Potential Effects of Climate Change on Air Quality

The atmospheric sciences community recognizes that climate and air quality are linked through atmospheric chemical, radiative, and dynamic processes at multiple scales (NRC, 2001). The results of a limited number of studies of the relationship between weather and ozone concentrations, the effects of temperature on atmospheric chemistry, and the sensitivity of emissions to weather and land use suggest that climate change could adversely affect air quality. However, the community's understanding of the many climate-air quality links is still very limited.

Ozone. An association between tropospheric ozone (O₃) concentrations and temperature has been demonstrated from measurements in outdoor smog chambers and from measurements in ambient air (USEPA, 1996). Chamber studies found a linear relationship between maximum O₃ and temperature (Kelly and Gunst, 1990). Numerous ambient studies done over more than a decade have reported that episodes of high temperatures characterize seasonally high O₃ years (see USEPA, 1996; NRC, 1991 for a summary of these studies). In general, an increase in atmospheric temperature accelerates photochemical reaction rates in the atmosphere and increases the rate at which tropospheric O₃ and other oxidants (e.g., hydroxyl radicals) are produced. However, O₃ levels do not always increase with an increase in temperature (e.g., when the ratio of VOCs to NO_x is low).

Ozone is expected to be influenced by wind speed because lower wind speeds should lead to reduced ventilation and the potential for greater buildup of O₃ and its precursors. Abnormally high temperatures are frequently associated with high barometric pressure, stagnant circulation, and suppressed vertical mixing resulting from subsidence (Mukammal et al., 1982), all of which may contribute to elevated O₃ levels. Increases in water vapor increase the potential for O₃ formation (Penner et al., 1989), as do frequent or intense high-pressure systems.

Climate change could reduce O₃ concentrations, however, by modifying factors that govern O₃-producing reactions (Smith and Tirpak, 1989; NRC, 1991); for example, a more vigorous hydrologic cycle could lead to an increase in cloudy days. More cloud cover, especially in the morning hours, could diminish reaction rates and thus lower O₃ formation.

Changes in meteorology are also likely to affect biogenic emission rates and evaporative emissions, in addition to altering rates of atmospheric chemical reactions and transport processes (see NRC 1991, EPA 1996). In particular, high temperatures cause increased VOC evaporative emissions when people fuel and run motor vehicles. The seasonal variation in natural emissions of VOCs and NO suggests that warmer temperatures are associated with increased natural emissions. For example, an increase of 10°C can cause over a 2-fold increase in both VOC and NO biogenic emissions (USEPA, 2000).

Higher outdoor temperatures will reduce the demand for heating services during winter and increase the demand for cooling services during summer. To the extent that these services are provided by fossil fuel combustion, emissions of associated pollutants, such as CO, NO_x, and VOCs will change. However, the overall net effect on future emissions, after taking into account future emissions controls, is unclear.

Sulfur Dioxide and Nitrogen Oxides. SO₂ and NO_x oxidize in the atmosphere to form sulfuric acid and nitric acid, respectively. These acids can be deposited to the earth's surface in "dry" form as gases or aerosols or "wet" as acid rain. Wet deposition is determined by the amount, duration, and location of precipitation and changes in the total acid levels, which are in turn determined by atmospheric chemistry and precipitation patterns (Martin, 1989; Smith and Tirpak, 1989). Although regional patterns of acid deposition are uncertain, many of the factors that affect O₃ formation also influence acid deposition (Penner et al., 1989; Smith and Tirpak, 1989). Higher temperatures accelerate the oxidation rates of SO₂ and NO_x to sulfuric

and nitric acids, increasing the potential for acid deposition.

If climate change results in a more vigorous hydrologic cycle and increased cloud cover, this may reduce rates of transformation from SO₂ to acidic materials, thus reducing the potential for acid deposition. Changes in circulation and precipitation patterns will affect transport of acidic materials, which in turn will determine the geographic location of acid deposition (Penner et al., 1989; Martin, 1989). Local, regional, and national air quality levels, therefore, will be partially determined by changes in circulation and precipitation patterns (Martin, 1989; Smith and Tirpak, 1989).

Particulate Matter. Secondary particles are formed from gases through chemical reactions in the atmosphere involving atmospheric oxygen and water vapor; reactive species such as ozone; radicals such as the hydroxyl and nitrate radicals; and pollutants such as SO₂, NO_x, and organic gases from natural and anthropogenic sources. In addition to these factors, secondary aerosol formation depends on atmospheric conditions, including solar radiation and relative humidity. As a result, the same meteorological processes that are noted above may affect fine particulate concentrations. In addition, natural particulate emissions (e.g., from wildfires and soil erosion) can also be affected by weather patterns such as droughts.

Atmospheric particles also play an important role in altering the amount of solar radiation transmitted through the Earth's atmosphere (i.e., radiative forcing). Particles, especially those containing sulfate, exert a direct effect by scattering incoming solar radiation back to space, thus providing a cooling effect. However, black carbon in particles absorbs solar radiation and consequently warms the atmosphere. The IPCC Third Assessment Report (IPCC, 2001) provides estimates of the net direct effect of aerosols on radiative forcing, but notes that there is much less confidence in these estimates relative to estimates for greenhouse gases.

Particles also exert an indirect effect on climate by affecting the size and number of

cloud droplets. As a result of these processes, clouds reflect more solar radiation back to space. These effects have been observed (e.g., cloud droplets in polluted areas tend to be smaller than those formed in clean areas). However, the magnitude of the overall indirect effects of aerosols on climate is very uncertain (IPCC, 2001).

Modeling Studies of Climate Change and Air Quality. Of the few modeling studies of regions in the U.S. that have quantified the effects of climate change on ambient concentrations, most have examined the impact of increased temperature on O₃ formation. Although these studies reveal O₃ concentrations increase as temperature rises, the estimated magnitude of the effect varies considerably. However, several of these studies relied on assumptions or held constant key variables such as emission levels, mixing heights, and cloudiness. As a result, these studies demonstrate the sensitivity of atmospheric air pollutants to changes in specific meteorological variables but cannot be viewed as projections of future changes in air quality. For example, these studies have not addressed such issues as changes in the frequency of stagnation episodes associated with high levels of observed ozone, future levels of emissions (important for non-linear processes), or changes in synoptic weather conditions.

In a preliminary study, Gery et al. (1987) examined the effects of increased temperature and decreased stratospheric O₃ on tropospheric O₃ formation in 15 separate combinations of city and meteorological episodes. The temperature effect (holding stratospheric O₃ constant) was found to increase ground-level O₃ by about 2-4% for a 2°C increase and by about 5-10% for a 5°C increase (p. 76). Morris et al. (1989) examined the effects of a uniform 4°C temperature increase and an attendant increase in water vapor concentration (assuming a constant relative humidity) on daily tropospheric O₃ concentrations. The model results indicated that changes in the highest daily O₃ concentrations could range from a decrease of -2.4% to an increase of 20%. A further study (Morris et al., 1991) examined a broader range

of reactivity conditions and used locally specific, model-predicted temperature changes corresponding to a doubled CO₂ experiment. The impact of temperature on biogenic hydrocarbon emissions was included. The study estimated the changes in VOC emission controls that would be needed to attain the O₃ NAAQS in each city. In all cases the needed controls increased approximately in proportion to the local increases in temperature.

In the most recent of these studies (Morris et al., 1995), a 4°C temperature perturbation was imposed uniformly on a region encompassing the Northeastern United States. The response of evaporative hydrocarbon emissions from motor vehicles to the temperature increase was also included in the analysis. The model simulations showed that under global warming conditions the concentrations of O₃ increased throughout the region. Incremental increases in O₃ concentration associated with the 4°C temperature increase ranged from about 28 parts per billion (ppb) (compared to 145 ppb O₃ without the 4°C increase) to 8 ppb (compared to about 27 ppb).

Hales (1988) used a storm-cloud model (PLUVIUS-2) to examine the impacts of a temperature increase on the production of acidic materials. The model results indicated that sulfate (SO₄) production increased by about 2.5 times for a 10°C increase in temperature. Gery et al. (1987) also show that a temperature increase would speed the formation of H₂O₂, increasing the conversion of SO₂ to sulfuric acid.

Conclusions

Changes in weather that may accompany climate change may affect atmospheric concentrations of air pollutants. Of particular concern are potential changes in O₃ and particulate matter concentrations. These pollutants cause a range of health and other effects, and air quality standards for these pollutants were exceeded in many areas. Ozone and secondary particulate matter are formed in the atmosphere and thus are influenced by prevailing meteorological

conditions. In addition, they are known to have important effects on the climate system. These linkages are complex and involve nonlinear processes. Because many parameters can change (e.g., emissions, climate variables, ultraviolet levels) more or less simultaneously, predicting future changes in air quality is a challenging task.

However, there is a great deal that is unknown with respect to climate change and air quality. There remains a basic need to conduct process studies to develop a better understanding of key relationships (e.g., sensitivity of biogenic emissions to changes in temperature). More fundamentally, better emission inventories and observational datasets are needed to analyze specific atmospheric processes. Ultimately, improving our understanding of interactions between climate change and air quality will require the ability to couple regional-scale air quality/climate models with global-scale climate and chemistry under a range of socioeconomic, emissions, and climate scenarios.

References

- Gery, MW, Edmond, RD, Whitten, GZ. 1987. Tropospheric Ultraviolet Radiation: Assessment of Existing Data and Effect on Ozone Formation. EPA/600/3-87/047. USEPA. Research Triangle Park, NC.
- Hales, J. 1988. Untitled. In: Sensitivity of Urban/Regional Chemistry to Climate Change: Report of the Workshop (Wuebbles DJ, Penner JE, eds). Lawrence Livermore National Laboratory, Livermore, CA.
- 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 (Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Jonhson CA, eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.
- Lamb, BK, Westber, HH, Quarles, T, Flyckt, DL. 1984. Natural Hydrocarbon Emission Rate

- Measurements from Selected Forest Sites. EPA-600/3-84-001. USEPA. Research Triangle Park, NC.
- Kelly, NA, Gunst, RF. 1990. Response of ozone to changes in hydrocarbon and nitrogen oxide concentrations in outdoor smog chambers filled with Los Angeles air. *Atmospheric Environment*, Part A 24: 2991-2005.
- Martin, HC. 1989. The linkages between climate change and acid rain. In: *Global Climate Change Linkages: Acid Rain, Air Quality, and Stratospheric Ozone* (White, JC, Wagner, W, Beale, CN, eds). Elsevier, New York, NY.
- Morris, RE, Gery, MS, Liu, MK, Moore, GE, Daly, C, Greenfield, SM. 1989. Sensitivity of a regional oxidant model to variations in climate parameters. In: *The Potential Effects of Global Climate Change on the United States* (Smith JB, Tirpak DA, eds). USEPA, Office of Policy, Planning and Evaluation. Washington, DC.
- Morris, RE, Whitten, GZ, Greenfield SM. 1991. Preliminary assessment of the effects of global climate change on tropospheric ozone concentrations. In: *Proceedings of the Specialty Conference: Tropospheric Ozone and the Environment II. Air & Waste Management Association*, p 5-30. Pittsburgh, PA.
- Morris RE, Guthrie PD, Knopes CA. 1995. Photochemical modeling analysis under global warming conditions. In: *Proceedings of the 88th Air & Waste Management Association Annual Meeting and Exhibition, Paper No. 95-WP-74B.02*. Air & Waste Management Association. Pittsburgh PA.
- Mukammal, EI, Neumann, HH, Gillespie, TJ. 1982. Meteorological conditions associated with ozone in southwestern Ontario, Canada. *Atmospheric Environment*, 16:2095-2106.
- NRC. 1991. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*. National Academy Press, 524 pg. Washington, DC.
- NRC. 2001. *Global Air Quality*. National Academy Press, 41 pg. Washington DC.
- Penner, JE, Connell, PS, Wuebbles, DJ, Covey, CC. 1989. Climate change and its interactions with air chemistry: perspective and research needs. In: *The Potential Effects of Global Climate Change on the United States* (Smith JB, Tirpak DA, eds). EPA/230-05-89-050. USEPA, Office of Policy, Planning and Evaluation. Washington, DC.
- Smith, JB, Tirpak, DA (eds). 1989. *The Potential Effects of Global Climate Change on the United States*. EPA-230-05-89-050. USEPA, Office of Policy, Planning and Evaluation. Washington, DC.
- USEPA. 1994. *Motor Vehicles and the 1990 Clean Air Act. Fact Sheet OMS-11*. EPA 400-F-92-013 (<http://www.epa.gov/otaq/11-vehs.htm>) USEPA. 1996. *Air Quality Criteria for Ozone and Related Photochemical Oxidants*. (EPA/600/P-93/004a-cF). U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, Washington, DC.
- USEPA. 2000. *National Air Pollutant Emission Trends: 1900-1998*. EPA 454/R-00-002. USEPA, Office of Air Quality Planning and Standards. Research Triangle Park, NC.
- USEPA. 2001a. *National Air Quality and Emissions Trends Report: 1999*. EPA-454/F-01-004. USEPA, Office of Air Quality Planning and Standards. Research Triangle Park, NC.
- USEPA. 2001b. *Latest Findings on National Air Quality: 2000 Status and Trends*. EPA-454/K-01-002. USEPA, Office of Air Quality Planning and Standards. Research Triangle Park, NC.
- USEPA. 2002. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*. EPA 430-R-02-003. USEPA, Office of Atmospheric Programs. Washington, DC.

¹ Estimates cited here are from various EPA reports, including the National Air Pollutant Emission Trends: 1900-1998 (USEPA, 2000), National Air Quality and Emissions Trends Report: 1999 (USEPA, 2001a) and Latest Findings on National Air Quality: 2000 Status and Trends (USEPA, 2001b). Electronic versions of these reports can be found at www.epa.gov/airtrends.

² Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg CO₂ Eq), which weight each gas by its Global Warming Potential (GWP) value.

³ International bunker fuels refer to fuels used by ships or aircraft for international transport activities. In accordance with greenhouse gas emission guidelines, emissions resulting from the combustion of international bunker fuels are reported separately and not included in national emissions totals. The Parties to the United Nations Framework Convention on Climate Change have yet to decide on a methodology for allocating these emissions between countries.

The views expressed in this paper are those of the author and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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