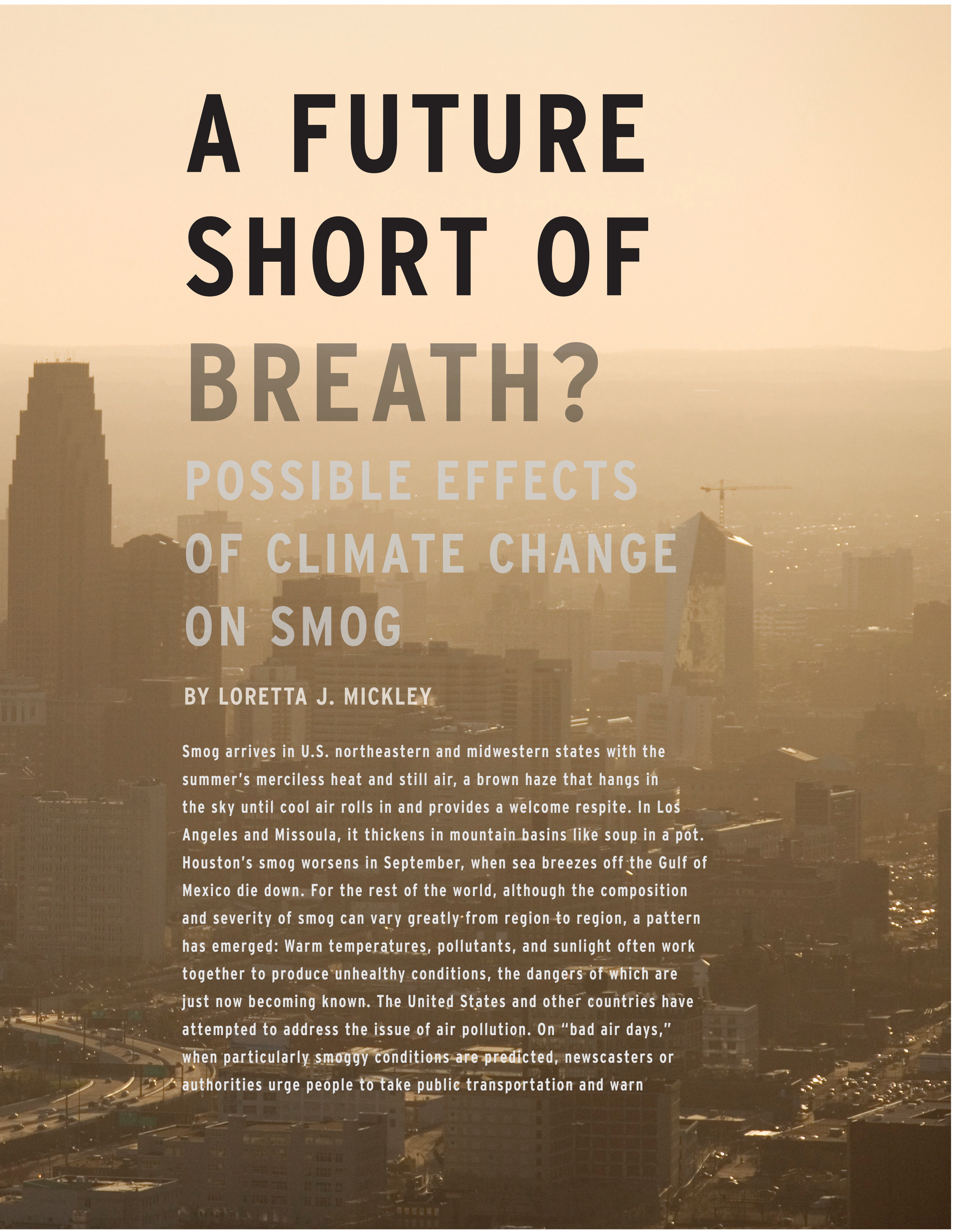


A FUTURE SHORT OF BREATH?

POSSIBLE EFFECTS OF CLIMATE CHANGE ON SMOG

BY LORETTA J. MICKLEY

Smog arrives in U.S. northeastern and midwestern states with the summer's merciless heat and still air, a brown haze that hangs in the sky until cool air rolls in and provides a welcome respite. In Los Angeles and Missoula, it thickens in mountain basins like soup in a pot. Houston's smog worsens in September, when sea breezes off the Gulf of Mexico die down. For the rest of the world, although the composition and severity of smog can vary greatly from region to region, a pattern has emerged: Warm temperatures, pollutants, and sunlight often work together to produce unhealthy conditions, the dangers of which are just now becoming known. The United States and other countries have attempted to address the issue of air pollution. On "bad air days," when particularly smoggy conditions are predicted, newscasters or authorities urge people to take public transportation and warn asthmatics and others with heart or lung conditions to stay indoors.[1]

As more has become known about what meteorological conditions favor smog formation, predictions for the next day's air quality have become increasingly accurate. But what about the long-term picture? In coming decades, climate change will likely have a large impact on temperatures at the Earth's surface and on day-to-day weather patterns. Will higher temperatures at the surface favor smog formation? Or will these higher surface temperatures contribute to lofting of the smoggy air toward higher layers of the atmosphere? How will changes in cloud cover impact surface air quality? If a warmer atmosphere can hold more water vapor, will cloud cover increase, thereby slowing down the production of smog? Finally, how will developing countries adopt new technologies without further degrading their air quality in a changing world?

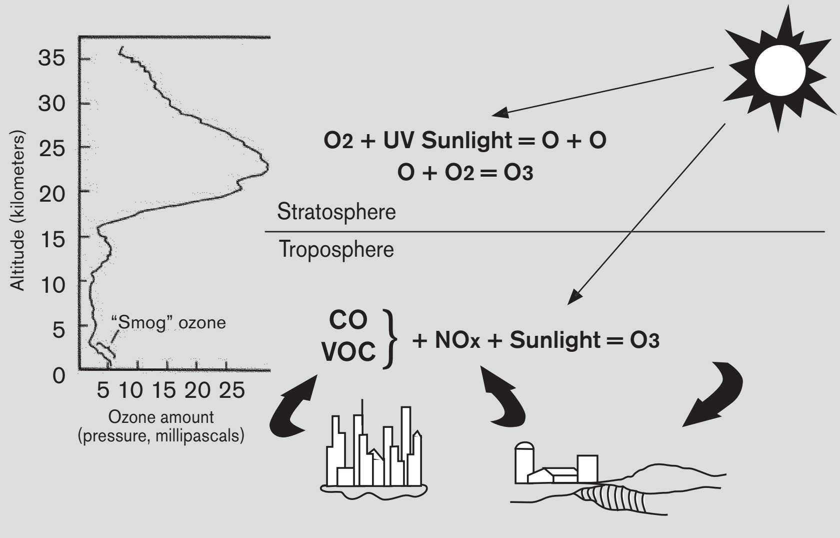
These are questions that are just now beginning to be addressed by the atmospheric chemistry community. The answers are important: In the United States, more than 100 million people live in areas that do not meet the U.S. Environmental Protection Agency's (EPA) minimum standards for air quality.[2] Europe loses 200 million working days a year to air pollution-related illness.[3] Worldwide, some researchers estimate that air pollution accounts for 800,000 premature deaths each year and 6.4 million years of life lost.[4] In recent decades, much work has been done to cut back the emissions of the precursors of smog. For example, across the U.S. Midwest from 1999 to 2003, power plants cut back the emissions of nitrogen oxides (NO_x), a main smog contributor, by a dramatic 40 percent.[5] Also, in the late 1990s, China reported a 25 percent drop in particle emissions, due in part to more stringent regulations, although in recent years, the trend may have leveled off.[6] However, a question remains whether coming climate change will diminish the effects of these programs to cut back smog. Research has pointed to an unforeseen but potentially serious impact of continuing trends in the emissions of greenhouse gases. These greenhouse gases are not directly harmful to human health in the small concentrations present in the atmosphere, but they could bring about conditions that favor production of other more dangerous pollutants like ozone and particulate matter.

What Is Smog?

Smog consists of a mixture of chemicals, some in gas-phase and some in the form of tiny particles. Smog starts with the emissions of gases like nitrogen oxides, volatile organic compounds (VOCs), and sulfur dioxide, and of particles like organic carbon and soot. Many of these constituents form during combustion processes. Every time someone starts a car or a coal-fired power plant kicks in, the high temperatures of combustion cause the release of more smog precursors into the air. But some smog precursors have natural sources. For example, for reasons that are not entirely clear, many trees and grasses emit VOCs like isoprene or a class of molecules called monoterpenes. Plant biologists are still trying to sort out why plants evolved to emit these chemicals and what protective effect the molecules could have on leaf structure. Even tiny organisms in soil emit high quantities of NO_x as they convert other forms of nitrogen into usable energy.

In the soup of smog, the two most deleterious chemicals are ozone and particles less than 2.5 millimeters in diameter (otherwise known as PM2.5). Ozone is a very reactive molecule, and once breathed in can damage lung tissue. Ozone can trigger asthma attacks or other respiratory diseases and can sensitize lung tissue to other irritants. Unlike the other gases mentioned so far, ozone is not emitted directly into the atmosphere but is a byproduct of the chemical reactions taking place there. In the troposphere, the lowest layer of the atmosphere, ozone is made via the oxidation of VOCs, methane, and carbon

Figure 1. Diagram of ozone formation



NOTE: In the troposphere, ozone (O_3) is formed through oxidation of chemicals such as carbon monoxide (CO) and volatile organic compounds (VOCs) in the presence of nitrogen oxides (NOx) and sunlight. These chemicals have anthropogenic and natural sources. In the stratosphere, O_3 is formed through the interaction of sunlight and molecular oxygen.

SOURCE: World Meteorological Organization, *Scientific Assessment of Ozone Depletion: 1998, WMO Global Ozone Research and Monitoring Project,* Report No. 44 (Geneva, 1998), http://www.esrl.noaa.gov/csd/assessments/1998/faq.html.

monoxide in the presence of NO_x and sunlight (see Figure 1 on page 36). (Note that tropospheric ozone pollution should not be confused with ozone in the stratosphere, which benefits humans; the box on this page differentiates the two.) In many regions, the anthropogenic emissions of NO_x together with the natural emissions of VOCs can work together to produce large quantities of ozone. This process is especially important in the U.S. Southeast. Elsewhere, biogenic emissions play a small role in smog formation.

Like ozone, PM2.5 can irritate lung tissue. Because these particles are so tiny, they can work their way deep into the lungs, unlike larger particles, which get trapped by the mucus lining in the airways. PM2.5 has been implicated in pulmonary and cardiovascular disease. Some PM2.5, called primary aerosol, is emitted directly into the atmosphere, like the soot from diesel engines. But much of PM2.5 is formed like ozone through chemical reactions of smog precursors. For example, some of the oxidation products of VOCs are not very volatile in the atmosphere and quickly condense to form particles called secondary organic aerosol. Sulfur dioxide, emitted largely from coal-fired power plants, rapidly oxidizes in the atmosphere to form sulfate particles. (The first box on page 39 provides more examples of particulate ingredients.)

Although episodes of high primary aerosol can occur throughout the year, most smog is a summertime phenomenon, because the photochemistry driving most smog formation depends on sunlight and high temperatures. The greater the amount of sunlight, the larger the concentrations of those highly reactive molecules that can catalyze smog formation. The higher the temperatures, the faster all the smog photochemical reactions will proceed. Also, at higher temperatures, the biosphere puts out more isoprene. Deciduous trees emit most of their VOCs in the spring and summer. The hot, stagnant conditions of summer, when there is little exchange of clear air with the rest of the atmosphere, are perfect for smog events. In these conditions, concentrations of ozone and PM2.5 can build to dangerous levels.

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California's air quality has improved due to strict curbs on emissions, although ozone and particulate matter are still significant problems in much of Southern California.

GROUND-LEVEL VERSUS STRATOSPHERIC OZONE

Ozone is a trace gas in the atmosphere, present in tiny concentrations. In the troposphere—that part of the atmosphere closest to the Earth's surface—ozone is bad for human health and bad for crops because it is a "sticky" molecule and can attach easily to leaves or human lungs, causing damage. While small amounts of ozone have probably been present in the troposphere for millennia, levels have increased dramatically over the last century due to the abundance of ozone precursors emitted by human activity.

In the stratosphere, the next layer up in the atmosphere, ozone filters out incoming ultraviolet sunlight, shielding the biosphere from these harmful wavelengths of light.

In recent decades, stratospheric ozone has been threatened by a class of chemicals known as chlorofluorocarbons, which are inert in the troposphere but decompose in the stratosphere. The most well-known sign of that threat is the "ozone hole," which appears over Antarctica in the spring. (A smaller one also forms over the Arctic in spring.)

Wherever it is found, an ozone molecule has always the same chemical formula: O_3.

Climate Change and Smog

The outlook for smog over the United States and elsewhere in the world is uncertain. Since the 1960s, despite some resistance, there has been a relatively steady push for clean air in the United States. (The second box on page 39 provides a brief outline of such efforts.) But these efforts may be undermined by coming climate change. In the developing world, which historically has had difficulty enforcing air pollution regulations, the net effect of climate change and continued emissions of soot and smog precursors could be quite hazardous.

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Smog occurs in Houston in September when temperatures are still high and the breeze off the Gulf of Mexico diminishes.

Temperature Effects

How will climate change affect surface air quality? The short answer is, as surface temperatures rise, the rates of photochemical reactions that lead to smog formation will accelerate. In addition, trees will also emit greater quantities of VOCs at higher temperatures, further enhancing concentrations of ozone and secondary organic aerosol.

To gauge the possible effects of increasing temperature on smog, scientists have studied the effect of heat waves in the recent past. One recent study examined the relationships of surface ozone concentrations and temperature in the summer across several regions—California, the southeastern United States, and the Northeast—for the 1980–1998 period.[7] The researchers found that the probability of exceeding the EPA ozone standard of 84 parts per billion (ppb) increased significantly with increasing temperature, particularly in the Northeast. There the probability jumped dramatically, from 5 percent at 84°F to 18 percent at 91°F, 42 percent at 98°F, and 66 percent at 104°F. In the 1980–1998 period, surface temperatures above 100°F rarely occurred. However, in the future, such temperatures may become more common.

But this short answer—that higher temperature means worsening air quality—neglects many competing and complicating factors. For example, the source gases that form secondary organic particles condense less readily at higher temperatures, which could mean fewer such particles in the atmosphere in the future.

The Effect of Stagnation

One of the main factors influencing pollution levels is the frequency and duration of stagnation episodes. Stagnant air traps air pollution, allowing the chemicals to interact and the products of emissions to accumulate. Stagnation episodes typically occur during the summer, when the heat and humidity can become unbearable, but they can occur at other times of the year as well. In December 1952, a cold air mass moved off the English Channel and parked over London for five days. The cold air trapped the plumes of soot emanating from coal-fired stoves and factories, leading to a thick, dirty haze. This smog event, known as the Great Smog of 1952, may have led to as many as 12,000 premature deaths in the days and months that followed.

In the coming decades, as climate changes, will such stagnation episodes take place more frequently? Will they last longer when they occur? To understand how future climate change could affect stagnation episodes, it is helpful to think about how such episodes in the present-day atmosphere come and go. Over midlatitudes, stagnation is one phase of an endlessly repeating weather pattern. First, a cold front comes through from the west, bringing rain and cool weather. After the passage of the cold front, winds weaken, the sky clears, and temperatures begin to climb. The air may stagnate. Soon another cold front arrives. A wedge of cool or cold air pushes in, lifting the warm (and possibly polluted) air eastward and poleward. What drives these cold fronts is the Earth's heat imbalance. The sun deposits most of its energy in the tropics, and the ocean and atmosphere respond with several mechanisms that redistribute that energy. Cold fronts contribute to this redistribution by pushing warm air toward the colder, higher latitudes.

New research suggests that cold fronts will appear less frequently over mid-latitudes in the future as the Earth warms in response to climate change.[8] The reason for this is twofold. First, high latitudes are expected to warm more quickly than the tropics in the future atmosphere due to feedbacks involving snow and ice cover. Over the past 100 years, average Arctic temperatures have already increased at almost twice the rate of the rest of the world. Second, in a warmer world, more of the redistribution of the Earth's energy can occur via transport of water vapor from the tropics poleward. One way to think of this is to imagine each molecule of water vapor as a packet of energy, representing the solar input that was required to evaporate it from the tropical ocean. A warmer atmosphere can hold more such energy packets, making the distribution of energy by other means, such as storms and cold fronts, less likely.

A decline in the number of cold fronts in a future world would likely spell more persistent stagnation episodes and worsening pollution. One recent study estimates that the effect of fewer cold fronts by 2050 could double the average length of pollution episodes in the Midwest from two to four days.

Other Climate Effects on Smog

The complex interplay of smog and meteorology makes it a challenge to forecast future smog levels much past a 5- or 10-year time frame in a warming world. Increased precipitation in some regions would efficiently flush out particles. Increased cloud cover would diminish the rates of the photochemical reactions that produce smog, since these reactions depend on sunlight. As the Earth's surface warms, increased turbulence could deepen the planetary boundary layer—the region of the troposphere that hugs the Earth's surface and into which air pollutants are first deposited.[9] A deeper planetary boundary layer would mean greater dilution of pollution and cleaner air.

Future smog in coastal cities would be particularly sensitive to changes in sea breeze strength or, on a larger scale, monsoon intensity. Sea breezes and monsoons are driven by the temperature contrast between land and ocean. For example, high inland temperatures over the Indian subcontinent in summer bring about monsoon winds and rain, which flush out pollution in the region. Most climate models predict increased rainfall in the summer monsoon season of South and Southeast Asia, thus easing pollution levels. The uncertainty in such predictions, however, is large.

Recent Predictions of Future Air Quality

Using state-of-the-art models, several research groups have begun investigating the effect of climate change on air qual-

A HISTORY OF U.S. AIR POLLUTION REGULATION

- 1940s: Serious smog events in Los Angeles and Donora, Pennsylvania, raised public awareness of the dangers of smog.
- 1950s: The Air Pollution Control Act of 1955 focused mainly on providing funding for research into the dangers of pollution.
- 1960s: The Clean Air Act of 1963 and subsequent amendments established standards for automobile emissions and emissions from industry and power plants.
- 1970s: The Clean Air Act of 1970 set the first National Ambient Air Quality Standards (NAAQS) for six air pollutants, including ozone and sulfur dioxide.
- 1980s: Little new legislation was passed.
- 1990s: The Clean Air Act of 1990 further tightened the regulations of the 1970 legislation, adding soot and lead and imposing stricter controls on emissions of nitrogen oxides from new automobiles and power plants.
- 2000s: The proposed Clear Skies legislation, which many experts believe would have weakened the Clean Air Act of 1990, died in Congress in 2005. The Clean Air Interstate Rule of 2005, which applies only to eastern states, put in place a cap-and-trade policy for pollutants and extended compliance deadlines past those of the Clean Air Act. Many environmentalists have praised the new rule, but some have criticized the relaxation of compliance deadlines.

A FIELD GUIDE TO PARTICLES

The particles in the atmosphere come from a plethora of sources, and a good deal of research is spent trying to understand these sources and the complicated ways that chemicals combine to form particles. Key constituents of particles and their sources include

- *sulfate* (SO_4^{2-}): from emissions of sulfur dioxide, which in turn comes mainly from coal-fired power plants; dissolved in rainwater, sulfate produces acid rain;
- *nitrates* (NO_3^-): from all power plants dependent on combustion, many industrial processes, and the combustion of gasoline and diesel fuel;
- *organic carbon*: from combustion of gasoline and diesel fuel, natural vegetation processes, the use of industrial solvents, and meat-cooking operations;
- *soot*: primarily from the combustion of diesel fuel in trucks, construction and agricultural equipment, locomotives, and ships; also from wood-burning stoves (and also known as black carbon or elemental carbon);
- *ammonium* (NH_4^+): mainly from agricultural operations such as cattle and hog farms and the application of fertilizer;
- *crustal materials*: from soil and rock dust (for example, oxides of silica, calcium, and iron); and
- *metals*: from industrial processes; includes lead, mercury, and copper.

One particle can be made up of many different chemicals, so a sulfate particle could also contain ammonium or nitrate. In the eastern United States, sulfate contributes about 50–60 percent of particle mass, due to the coal-fired power plants in that region. In the Midwest and California, nitrate is a major component of airborne particles.

ity.[10] These studies are very computer intensive, sometimes requiring months of simulation time (the box on page 40 discusses such models). So far, most efforts have focused on the response of ozone concentrations to climate change in the United States and also Europe, with little attention yet paid to future air quality in developing countries. Studies on how particulate matter will respond to climate change are just now beginning.

Most studies have estimated significant increases in peak summertime ozone concentrations in the midwestern and northeastern United States (see Figure 2 on page 42). For example, some studies estimate that climate change in this region could increase daily average peak ozone concentrations by as much as 5 ppb by 2050, enough to tip the air quality index from "moderate" to "unhealthy" levels.[11] Another study found that during pollution episodes in the Midwest and Northeast, ozone concentrations could jump by as much as 10 ppb in the future climate.[12] Still another study showed that the impact of climate change on ozone concentrations over this region could be mitigated significantly if trends in energy use followed a less fossil-fuel intensive scenario.[13] Far less agreement in future ozone air quality has been found for the southeastern United States than for other regions: Some models predict much greater ozone levels for the Southeast by 2050,[14] while others predict relatively stable concentrations.[15] Part of the uncertainty here has to do with the limited knowledge regarding the fate of VOCs emitted by the abundant vegetation in this region. Also, if climate change enhances the flux of marine air into the Southeast, as some studies suggest, the result would in fact be cleaner air. In the western United States, ozone has so far appeared relatively insensitive to climate change.[16] For Europe, recent studies have forecast an increase in summertime surface ozone with climate change by 2030 or 2050.[17]

For particles, one pilot study for southern California found that a uniform increase in temperature of about 4ºF would decrease average PM2.5 concentrations by about 10 percent by making gas-phase precursors less likely to condense.[18] In that study, only changes in temperature were considered, although in a warming world, temperature change will be accompanied by a suite of other changing meteorological variables.[19] In one study that took into account the full picture of changing meteorology, researchers showed increased particle concentrations over northern Africa and southern Europe due to decreased precipitation, which washes out particles.[20] But precipitation is itself very hard to forecast.[21]

It should be emphasized, however, that all the studies described above made one very large assumption: that the emissions of smog precursors related to human activity would stay constant through future decades. In fact, it is quite possible that such emissions will decline, as new technology is put in place and existing regulations on pollution are tightened. The main value of these studies is that they make clear the climate change penalty that will be needed to overcome to meet air quality standards.

Feedbacks of Ozone and Particles on to Climate

It is clear that climate change will influence smog formation. What may be surprising is that ozone and PM can have

MODELING FUTURE AIR QUALITY

Beginning in the 1970s, scientists have relied on three-dimensional climate models to understand the atmosphere and predict the influence of greenhouse gases.[1] These models, whose origins can be traced back to the weather models of the 1950s, use mathematical equations to describe such phenomena as the motions of the atmosphere, the transfer of sunlight and heat through the atmosphere, and the water cycle. Some features of the Earth-atmosphere system can be specified, such as the arrangement of coasts and mountains, the amount of sunlight reaching the top of the atmosphere, or the emissions of greenhouse gases. The atmosphere in these models is divided up into thousands of gridboxes, not unlike a cake. As the model cycles through a model day, it calculates the weather in each gridbox and moves masses of air and moisture from box to box.

Chemical schemes for calculating ozone and particles can be implemented in these climate models or somehow linked to them.[2] The gridboxes in most global models cover large areas, sometimes thousands of square miles each. To obtain a more detailed look at pollution episodes, the results from global models can be downscaled using regional models with much smaller gridboxes covering a few dozen or hundred square miles each.[3]

These ensembles of models require vast computing resources. A typical simulation of one summer's chemistry in a regional model can take several weeks of computing time. A simpler approach has recently been explored using observed relationships of surface ozone and daily maximum temperatures. High levels of ozone correlate strongly with high temperatures, reflecting the combined effects of biogenic VOC emissions, temperature-driven photochemistry, and stagnation. By applying observed ozone-temperature relationships to future temperatures calculated by a climate model, scientists can bypass the time-consuming calculations of chemical models.[4]

1. See, for example, J. Hansen et al., "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model," *Journal of Geophysical Res*earch 93 (1988): 9341–64; J. Hansen et al., "Efficacy of Climate Forcings," *Journal of Geophysical Research* 110, no. D18104 (2005): doi:10.1029/2005JD005776; and G. A. Meehl et al., "Global Climate Projections," in IPCC, *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2007).

2. See, for example, L. J. Mickley et al., "Radiative Forcing from Tropospheric Ozone Calculated with a Unified Chemistry-Climate Model," *Journal of Geophysical Research* 104, no. D23 (1999): 30153–72.

3. See, for example, C. Hogrefe et al., "Simulating Changes in Regional Air Pollution over the Eastern United States Due to Changes in Global and Regional Climate and Emissions, *Journal of Geophysical Research* 109, no. D22301 (2004): doi:10.1029/2004JD004690.

4. C-Y. C. Lin, L. J. Mickley, K. Hayhoe, E. P. Maurer, and C. Hogrefe, "Rapid Calculation of Future Trends in Ozone Exceedances over the Northeast United States : Results from Three Models and Two Scenarios," poster presented at the EPA Progress Review Meeting: Consequences of Global Change for Air Quality Festival, Research Triangle Park, NC, February 2007.

large impacts on climate itself. Ozone is itself a greenhouse gas. Like the more well-known greenhouse gases carbon dioxide and methane, ozone absorbs the infrared radiation upwelling from the Earth's surface and acts like a kind of blanket, warming the Earth. It is estimated that increases in tropospheric ozone since the preindustrial era have contributed about one-fourth to one-third the warming effect of carbon dioxide.[22]

Particles have a more complicated role influencing climate. Most particles, such as sulfate or organic particles, reflect incoming sunlight like tiny mirrors and therefore lead to cooling. Soot particles, on the other hand, absorb incoming sunlight and outgoing infrared radiation, making the net effect of these particles difficult to calculate. Some studies have suggested that plumes of soot and sulfate particles emanating from South Asia may have led to local cooling of the Indian subcontinent, diminishing the strength of summer monsoon. This effect could counteract the warming influence of greenhouse gases, which most models predict will intensify the monsoon.

Particles can also influence climate indirectly, by providing nuclei upon which cloud water can condense. Through increasing the number of available condensation nuclei in the atmosphere, particles lead to longer-lived and brighter, more reflective clouds, thus also contributing to cooling of the atmosphere. According to some estimates, the warming effects of carbon dioxide alone are nearly balanced by the net cooling effects of particles.[23]

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Enforcing air quality legislation has proven difficult for many developing countries, but an alternative fuel initiative in Delhi successfully reduced some key pollutants.

Health Impacts of Pollution and Recent Policy

High levels of surface ozone and particles have been implicated in many diseases involving the cardiac and respiratory systems. Ozone can inhibit lung function and can trigger asthma attacks. In the United Kingdom during the August 2003 heatwave, thousands of people suffered from ozone-related lung diseases and as many as 600 people may have died because of the effects of high levels of ozone. Other cities in Europe also saw large increases in ozone-related illness and death during this heatwave.

For particles, evidence of links between high concentrations and ill health is becoming quite strong. One study showed an increased risk of atherosclerosis in people who had experienced long-term exposure to particles.[24] In another study, involving several hundred thousand people across the United States over a period of 18 years, exposure to particles was estimated by the participants' zip code addresses.[25] Using this vast amount of data, researchers found that each 10 gram per square meter of rise in PM2.5 levels was associated with 10–20 percent increases in mortality risk, comparable to or even larger than the risks associated with smoking. Finally, as with cigarette smoke, high concentrations of PM2.5 in outdoor air have been linked to ear infections in children under the age of two.[26]

In the United States, significant efforts to cut back emissions of smog precursors were made in the final decades of the twentieth century in response to the Clean Air Act and its amendments. Between 1980 and 1995, manmade VOC emissions declined by 15 percent. During the same time interval, NO_x emissions remained constant, even though the annual number of miles driven by cars and trucks increased 60 percent.[27] Since 1999, emissions of nitrogen oxides from power plants in the Midwest have fallen 40 percent.[28] Trends in NO_x emissions from traffic during this time period may have held steady,[29] or they may in fact be rising.[30] The signal is not clear.

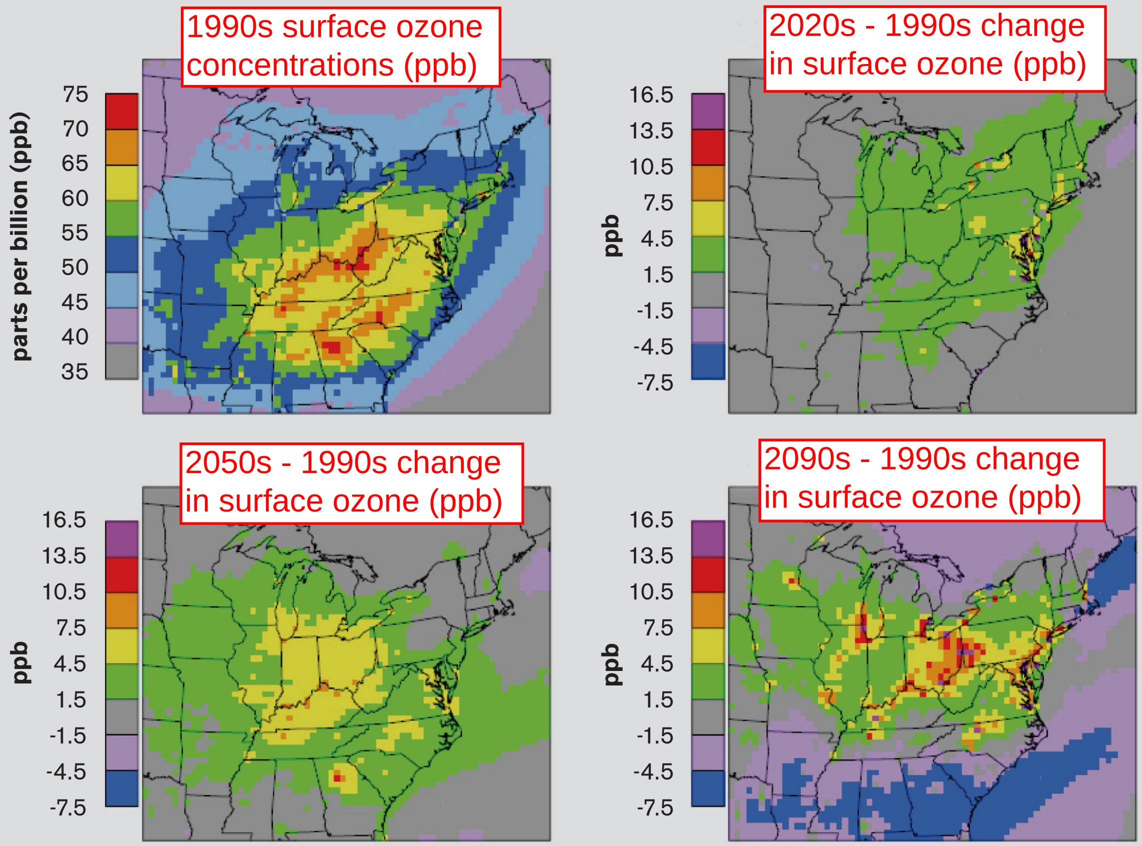
Conclusions: Overcoming the Climate Change Penalty

As climate changes in the coming decades, so will the daily weather patterns that influence day-to-day air pollution. While some regions could actually see improved air quality, many regions are expected to suffer a degradation of air quality due to a combination of higher surface temperatures, more persistent stagnation, or increased emissions of temperature-dependent VOCs from vegetation. Because the health impacts of even an incremental increase in ozone or particle concentrations could be large, the issue of climate change and smog warrants our close attention.

In the developed world, many programs are already in place for controlling the anthropogenic emissions of smog and its precursors. New research investigating the interaction between smog and climate underscores the importance of these programs. In the developing world, where enforcing the existing air pollution regulations has proven very challenging, the outlook is uncertain. For example, when climate change and likely trends in smog emissions are taken into account in model studies, surface ozone concentrations over India, China, and parts of Africa and South America show large increases in the summertime—up to 10 ppb, on average, by 2050. By 2100, according to the most pessimistic scenario for future global change, a large swath extending from eastern Africa across Asia to China could see increases of more than 30 ppb of ozone in July. Given the high population in this region, such increases could translate into tens of thousands of illnesses and premature deaths.[31]

To meet future air quality goals, policymakers in many regions will need to overcome what is now being called the "climate change penalty"; that is, the exacerbation of surface ozone levels by higher temperatures and increased stagnation episodes in a warmer world. Further research using multiple climate and precursor scenarios will help bracket the range of air quality responses expected in the coming decades. Such studies will enable policymakers to improve their long-term planning of air quality management. Because the precursors to pollution can be transported across boundaries and even oceans, international cooperation will likely be necessary to achieve local air quality goals. Finally, research into the impacts of climate change

Figure 2. Summertime average daily maximum 8-hour ozone concentrations for the 1990s and projected changes in concentrations for the 2020s, 2050s, and 2080s



NOTE: All results were calculated using a regional chemistry model, using present-day emissions of ozone precursors. Five consecutive summer seasons were simulated in each decade. The plots show the effect of climate change on ozone smog, in the absence of further restrictions on emissions of ozone precursors.

SOURCE: C. Hogrefe, B. Lynn, K. Civerolo, J.-Y. Ku, J. Rosenthal, C. Rosenzweig, R. Goldberg, S. Gaffin, K. Knowlton, and P. L. Kinney, "Simulating Changes in Regional Air Pollution over the Eastern United States due to Changes in Global and Regional Climate and Emissions," *Journal of Geophysical Research*, 109, D22301, doi:10.1029/2004JD004690, 17 November 2004. Copyright 2004 American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.

on smog can provide further motivation for controlling the growth of greenhouse gas emissions in coming decades. Along with many of the other probable consequences of climate change—including increased likelihood of drought, tropical disease, and rising sea levels—it is becoming clear that we need to take into account the health impacts of more intense or more persistent smog episodes.

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A sunrise in Detroit, where ozone pollution has decreased somewhat in recent years but particulates remain at high levels.

NOTES

1. For example, the U.S. National Weather Service provides air quality forecasts (see http://www.weather.gov/aq/), as does the U.K. Met Office (see http://www.metoffice.gov.uk/environment/aq/index.html). Other examples can be found by region through the World Meteorological Organization members, http://www.wmo.ch/pages/members/index_en.html.

2. U.S. Environmental Protection Agency, *Report on Air Quality in Nonattainment Areas for 2003–2005 Covering Ozone, Particulate Matter, Carbon Monoxide, Sulfur Dioxide, Nitrogen Dioxide, and Lead: Technical Summary* (Research Triangle Park, NC, 2006).

3. European Environment Agency (EEA), *The European Environment: State and Outlook 2005* (Copenhagen: EEA, 2005).

4. A. J. Cohen et al., "The Global Burden of Disease Due to Outdoor Air Pollution, *Journal of Toxicology and Environmental Health, Part A* 68 (2005): 1301–07.

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6. M. S. Ho and C. P. Nielsen, eds., *Clearing the Air: The Health and Economic Damages of Air Pollution in China* (Cambridge, MA: MIT, 2007).

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