

**Second  
Edition**

# **AIR POLLUTION AND GLOBAL WARMING**

**HISTORY, SCIENCE,  
AND SOLUTIONS**

**Mark Z. Jacobson**



# Air Pollution and Global Warming

## *History, Science, and Solutions*

Second Edition

Mark Z. Jacobson  
Stanford University



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Cover photograph: Late afternoon sunlight peering through smoke billowing from a power plant against the backdrop of a sky enhanced in its redness by air pollution. (Photo taken on December 10, 2009, by Mikhail Didarev/Dreamstime.com)

## Air Pollution and Global Warming

*History, Science, and Solutions*

Second Edition

This new edition of Mark Z. Jacobson's textbook provides a comprehensive introduction to the history and science of the major air pollution and climate problems that face the world today, as well as the energy and policy solutions to those problems. Every chapter has been updated with new data, figures, and text. There is also a new chapter on large-scale solutions to global warming and air pollution. Color photographs, diagrams, examples, and homework problems have also been added. This is an ideal introductory textbook on air pollution and global warming for students taking courses in atmospheric chemistry and physics, meteorology, environmental science, earth science, civil and environmental engineering, chemistry, environmental law and politics, and city planning and regulation. It also forms a valuable reference text for researchers and an introduction to the subject for general audiences.

Mark Z. Jacobson is Director of the Atmosphere/Energy Program and Professor of Civil and Environmental Engineering at Stanford University. He is also a Senior Fellow of the Woods Institute for the Environment and of the Precourt Institute for Energy. Professor Jacobson has been on the faculty at Stanford since 1994. His research involves the development and application of numerical models to understand the effects of energy and transportation systems on climate and air pollution and the analysis of renewable energy resources. Professor Jacobson received the 2005 American Meteorological Society Henry G. Houghton Award, based in part on his discovery that black carbon may be the second leading cause of global warming after carbon dioxide. He coauthored a 2009 cover article in *Scientific American* (with Dr. Mark Delucchi) on how to power the world with renewable energy. In 2010, Professor Jacobson was appointed to the Energy Efficiency and Renewables Advisory Committee by the U.S. Secretary of Energy. He has taught courses on atmospheric pollution and climate, weather and storms, air pollution modeling, and numerical weather prediction. Professor Jacobson has also published more than 120 peer-reviewed journal articles and the textbook *Fundamentals of Atmospheric Modeling* (2nd edition, 2005; Cambridge University Press).

## Praise for *Air Pollution and Global Warming*, 2nd edition

“Although there are many texts devoted to the topic of air pollution, in my opinion a gap exists between texts that focus primarily on atmospheric chemistry and those that focus on air pollution control engineering. *Air Pollution and Global Warming* fills this gap nicely by taking an inclusive approach that gives students a broad understanding of the causes and consequences of air pollution. The sources and transformation of air pollutants, health effects, regulatory measures, and environmental consequences ranging from acid deposition to climate change are addressed in a manner that is accessible to undergraduate students yet includes sufficient quantitative detail to enable in-depth analysis of the subject matter. I also appreciate the use of real-world data throughout the text to illustrate concepts and emphasize the relevance of the material. The concluding chapter on energy use is a welcome addition. . . . Students would be well served to have a sound understanding of the relevant issues, and the author provides this by identifying the magnitude of the problem, explaining the limitations of several popular but impractical proposals, and finally describing the most promising solutions. The author gives students the information they need to be informed decision makers in the future. Overall, the second edition has been thoughtfully updated to reflect the latest trends and research in the fields of air pollution and climate change. I appreciate the updated graphics and additional photos that make the second edition more visually appealing.”

– *Derek J. Straub, Department of Earth and Environmental Sciences, Susquehanna University*

“Mark Jacobson’s book provides a unique integrated introduction to atmospheric science, the science and adverse impacts of air pollution and climate change, and the regulations that address them. He provides an inspirational vision of how a conversion of the global energy system from fossil fuel to highly efficient wind, water, and solar power is technically feasible by 2050 and would greatly reduce future air pollution and climate change.”

– *Denise L. Mauzerall, Woodrow Wilson School of Public and International Affairs and Department of Civil and Environmental Engineering, Princeton University*

“Mark Jacobson presents an excellent overview of many facets of air pollution and global warming science. It’s an excellent reference for students and professionals.”

– *Jonathan D. W. Kahl, Professor of Atmospheric Science, University of Wisconsin–Milwaukee*

“An excellent textbook to introduce students with a basic scientific background to some of the most imminent issues of our time – air pollution and global warming – and how to address them in terms of both regulations and technological solutions. This new edition improves on its popular predecessor *Atmospheric Pollution* by not only updating its content but by providing information on how to technologically tackle air pollution problems and global warming issues. . . . a perfect companion for undergraduate- and graduate-level courses in atmospheric chemistry, atmospheric sciences, meteorology, and environmental sciences. . . . numerous homework problems will help make students aware of the complexity of air pollution and global warming issues.”

– *Daniel A. Knopf, School of Marine and Atmospheric Sciences, The State University of New York, Stony Brook*

## Praise for the previous edition, *Atmospheric Pollution: History, Science, and Regulation*

“ . . . one of the standard texts in this field, especially for environmental science courses at undergraduate and postgraduate levels, as well as a general reference and sourcebook for anybody interested in the history of airborne pollutants and their study, pollution meteorologists and atmospheric chemists.”

– *Weather*

“ . . . highly valued in environmental science curricula for its integrated approach to the scientific dimensions of all aspects of the atmospheric environment . . . ”

– *Chemical Heritage*

“ . . . well suited for individuals or courses with an interest in the history of air pollution science and regulation.”

– *EOS*

“ . . . a well-rounded introduction to problems of the atmosphere and offers rich material for students contemplating their solutions . . . ”

– *Physics Today*

## Foreword

Atmospheric chemistry, as a modern discipline, can be considered to have originated in 1931, when Sydney Chapman, distinguished British physicist, formulated a chemical mechanism for the formation of stratospheric ozone. The foundations of understanding tropospheric chemistry were laid in the early 1950s by Arie Haagen-Smit, a bioorganic chemist at the California Institute of Technology, who described ozone formation in the Los Angeles Basin as resulting from reactions involving volatile organic compounds and oxides of nitrogen. The essential reactive species in tropospheric chemistry remained unknown until the early 1970s, when the central role of the hydroxyl radical as the troposphere's "detergent" was revealed. The existence of particles in the air (aerosols) had long been recognized, but it was not until the past 50 years that instrumentation was developed that is capable of determining the size distribution and composition of atmospheric aerosols.

Threats to stratospheric ozone made headlines in the early 1970s, when Harold Johnston at the University of California, Berkeley, published calculations of the effect on stratospheric ozone of a proposed fleet of supersonic aircraft. Johnston's work was followed shortly thereafter by the revelation of the stratospheric chemical impact of chlorofluorocarbons, widely used as refrigerants and in consumer products, by F. Sherwood Rowland and Mario Molina of the University of California, Irvine. For their penetrating insights into atmospheric chemistry, Rowland, Molina, and Paul Crutzen of the Max Planck Institute for Chemistry in Mainz, Germany, received the 1995 Nobel Prize in Chemistry.

Mathematical models that describe the three-dimensional transport and chemistry in the atmosphere were first developed in the early 1970s. Such computer models have played a key role in representing our understanding of atmospheric processes and in planning emission controls to achieve desired levels of air quality. Three-dimensional numerical atmospheric chemical transport models are mandated in the U.S. Clean Air Act as the tool that must be used to design emission control strategies to attain national ambient air quality standards in urban and regional areas. Virtually all aspects of atmospheric chemistry and physics are now embodied in these models.

Humans have been concerned with weather and climate for millennia. Over geologic time, the Earth's climate variations have been a result of changes in the Earth's orbit, in the sun's output, or of volcanic eruptions that inject large amounts of material into the atmosphere. Although warming of the Earth by an increase of atmospheric CO<sub>2</sub> was calculated in 1896 by Svante Arrhenius, it was not until 1958 that David Keeling of the Scripps Institute of Oceanography began making precise measurements of atmospheric CO<sub>2</sub> at the top of Hawaii's Mauna Loa Volcano. The continuous record of CO<sub>2</sub> measurements on Mauna Loa, now overseen by the U.S. National Oceanographic and Atmospheric Administration (NOAA), constitutes the most profound environmental dataset in existence. That CO<sub>2</sub> record, when reconciled with estimates of CO<sub>2</sub> emissions from fossil fuel burning, establishes the unequivocal effect of humans on Earth's climate over the past 60 years.

Atmospheric science now involves thousands of scientists, in academic disciplines ranging over physics, chemistry, engineering, and health sciences. Writing an introductory text that spans the important components of atmospheric science, air pollution, climate, and effects is a daunting task indeed. Professor Mark Z. Jacobson has produced a text of remarkable breadth, one that can be appreciated by first-year college students and professionals alike. The book is alive with historical vignettes, photos, and figures. The reader gains an appreciation of the elegance of the science of the atmosphere, as well as of the role of humans in perturbing the atmosphere's composition and the effects of those perturbations. It is a pleasure to recommend this book to those with an interest in understanding Earth's precious atmosphere.

John H. Seinfeld  
Louis E. Nohl Professor  
California Institute of Technology

## Preface

Natural air pollution problems on the Earth are as old as the planet itself. Volcanos, fumaroles, natural fires, and desert dust have all contributed to natural air pollution. Humans first emitted air pollutants when they burned wood and cleared land (increasing wind-blown dust). More recently, the burning of coal, chemicals, oil, gasoline, kerosene, diesel, jet and alcohol fuel, natural gas, biomass, and waste, as well as the release of chemicals into the environment, have contributed to several major air pollution problems on a range of spatial scales. These problems include outdoor urban smog, indoor air pollution, acid deposition, the Antarctic ozone hole, global stratospheric ozone reduction, and global warming.

**Urban smog** is characterized by the outdoor buildup of gases and particles that are either emitted from vehicles, homes, industrial facilities, power plants, incinerators, or land-clearing and natural fires or formed chemically in the air from emitted pollutants. Smog affects human and animal health, structures, and vegetation. Urban smog occurs over scales of meters to hundreds of kilometers.

**Indoor air pollution** results from the emission of pollutant gases and particles in enclosed buildings and the transport of pollutants from outdoors to indoors. Worldwide, indoor air pollution is responsible for about 1.6 million premature deaths per year, mostly from the burning of wood, animal and agricultural waste, and coal for home heating and cooking in developing countries. Indoor air pollution occurs over scales of meters to tens of meters.

**Acid deposition** occurs when sulfuric, nitric, or hydrochloric acids in the air deposit to the ground as a gas or dissolve in rainwater, fog water, or particles.

Acids harm soils, lakes, forests, and structures. In high concentrations, they can also harm humans. Acid deposition occurs over scales of tens to thousands of kilometers.

The **Antarctic ozone hole** and **global stratospheric ozone reduction** are caused, to a large extent, by human-produced chlorine and bromine compounds that are emitted into the air and break down only after they have traveled to the upper atmosphere (the stratosphere). Ozone reduction increases the intensity of ultraviolet (UV) radiation from the sun reaching the ground. Intense UV radiation destroys microorganisms on the surface of the Earth and causes skin cancer in humans and animals. The Antarctic ozone hole occurs over a region the size of North America. Global stratospheric ozone reduction occurs globally.

**Global warming** is the increase in lower atmospheric (tropospheric) global temperatures and the resulting increase in ice melt, sea level, coastal flooding, heat stress, air pollution, malaria, influenza, severe storminess, and starvation due to shifts in agriculture caused by human emission of both greenhouse gases and particles. Greenhouse gases include carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. Major particle constituents contributing to global warming include black and brown carbon. Global warming is a global problem with regional impact.

Air is not owned privately; instead, it is common property (accessible to all individuals). As a result, air has historically been polluted without limit. This is the classic **tragedy of the commons**. The only known mechanism of limiting air pollution, aside from volunteerism and the fortuitous development of inexpensive, clean technologies, is government intervention. Intervention can take the form of setting up economic markets for the rights to emit pollution, providing subsidies for the development and implementation of clean technologies, limiting emissions from specific sources, requiring certain emission control technologies, or setting limits on pollutant concentrations and allowing the use of any emission reduction method to meet those limits.

Because government action usually requires consensus that a problem exists, the problem is severe enough to warrant action, and action taken will not have its own set of adverse consequences (usually economic), national governments did not act aggressively to control global air pollution problems until the 1970s and 1980s. For the most part, action was not taken earlier because lawmakers were not always convinced of the severity

of air pollution problems. Even when problems were recognized, action was often delayed because industries used their political strength to oppose government intervention. Even today, government intervention is opposed by many industries and politicians out of often misplaced concern that intervention will cause adverse economic consequences. In many developing countries, intervention is sometimes opposed because of the concern that developed countries are trying to inhibit economic expansion of the less developed countries. In other cases, pollution is not regulated strictly due to the perceived cost of emission control technologies and enforcement.

Despite the opposition to government intervention, such intervention has proven effective in mitigating various major air pollution problems facing humanity in some countries or on a global scale. For example, outdoor and indoor air pollution and acid deposition in many industrialized countries, including the United States, Japan, and most European countries, have decreased since the 1970s due to the development and use of emission control technologies and more efficient devices. However, such problems have increased in most of the rest of the world due to rapidly rising populations, higher energy demand, and low transfer rates of emission control technologies. Indoor air pollution, in particular, has become more severe in developing countries as populations have expanded and indoor burning of fuel for heating and cooking has continued.

The main cause of the Antarctic ozone hole and stratospheric ozone reduction, the emissions of classes of chemical compounds called chlorofluorocarbons and bromocarbons, has been substantially addressed. However, stratospheric ozone levels continue to stay low, in part due to the long lifetime of existing chlorofluorocarbons and partly due to global warming, which warms the lower atmosphere (the troposphere) but cools the stratosphere. Stratospheric cooling exacerbates damage to the ozone layer caused by chlorofluorocarbons and bromocarbons.

Addressing the problem of global warming is a process in its infancy. Despite modest efforts, emissions and global temperatures continue to rise rapidly. The consequences of higher temperatures are readily visible. The solution to global warming, although clear-cut in concept, is the challenge for the current and future generations.

This book discusses the history and science of major air pollution problems, the consequences of these problems, and efforts to control the problems through government intervention and existing clean technologies. The book then presents a proposed solution to global warming and air pollution, namely, the conversion of the world's energy infrastructure to a large-scale, clean, renewable one. Because air pollution and global warming, in particular, are so severe, a rapid and large-scale conversion is needed. *The main barriers to conversion are not technical, resource based, or even economic. Instead, they are social and political.*

The book synthesizes knowledge in the fields of chemistry, meteorology, radiation science, aerosol sciences, cloud physics, soil science, microbiology, epidemiology, energy, materials science, economics, policy, and law. The study of air pollution and climate is truly interdisciplinary.

This book is directed at students in environmental, Earth, atmospheric, and energy sciences; engineering; and policy. It was designed to be general enough for the interested layperson, yet detailed enough to be used as a reference text. The text uses chemical symbols and chemical equations, but all chemistry required is introduced in Chapter 1. No previous knowledge of chemistry is needed. The text also describes a handful of physical laws. No calculus, geometry, or higher math is needed.

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I want to thank several colleagues who reviewed different sections of this text. In particular, I am indebted to (in alphabetical order) Cristina Archer, Mary Cameron, Joe Cassmassi, Andrew Chang, Mark Delucchi, Frank Freedman, Ann Fridlind, Elaine Hart, Lynn Hildemann, Gerard Ketefian, Jinyou Liang, Nesrin Ozalp, Ana Sandoval, Roberto San Jose, Alfred Spormann, Amy Stuart, Azadeh Tabazadeh, John ten Hoeve, Daniel Whitt, and Yang Zhang, all of whom provided comments, suggestions, and/or corrections relating to the text. I also want to show my gratitude to Jill Nomura, Daniel and Dionna Jacobson, William Jacobson, and Yvonne Jacobson for helping with graphics and/or editing, as well as to the students who have used this text and then provided suggestions and corrections. Finally, I want to thank several anonymous reviewers, in particular one who provided many inspirational comments.





## Air Pollution and Global Warming

The relationship between air pollution and global warming is a complex one. Air pollution, particularly greenhouse gases like carbon dioxide, is a major driver of global warming. Conversely, global warming can lead to increased air pollution through various mechanisms, such as increased evaporation and changes in atmospheric circulation. This section explores the interplay between these two environmental issues.

Understanding the connection between air pollution and global warming is crucial for developing effective strategies to mitigate their impacts. This section discusses the scientific basis of this relationship and the role of human activities in exacerbating both problems.

# Brief Contents

1	Basics and Discovery of Atmospheric Chemicals	1
2	The Sun, the Earth, and the Evolution of the Earth's Atmosphere	29
3	Structure and Composition of the Present-Day Atmosphere	45
4	Urban Air Pollution	73
5	Aerosol Particles in the Polluted and Global Atmosphere	101
6	Effects of Meteorology on Air Pollution	127
7	Effects of Pollution on Visibility, Ultraviolet Radiation, and Colors in the Sky	153
8	International Regulation of Urban Smog Since the 1940s	175
9	Indoor Air Pollution	207
10	Acid Deposition	221
11	Global Stratospheric Ozone Reduction	237
12	The Greenhouse Effect and Global Warming	263
13	Energy Solutions to Air Pollution and Global Warming	309

# Contents

Foreword by John H. Seinfeld	page xv
Preface	xvii
<b>1 Basics and Discovery of Atmospheric Chemicals</b>	<b>1</b>
1.1. Basic Definitions	1
1.1.1. <i>Atoms, Elements, Molecules, and Compounds</i>	1
1.1.2. <i>Gases and Particles</i>	2
1.2. History of Discovery of Elements and Compounds of Atmospheric Importance	3
1.2.1. <i>Solids and Liquids, Ancient World–1690</i>	3
1.2.2. <i>Studies of Gases in the Air, 1450–1790</i>	12
1.2.3. <i>Discoveries after 1790</i>	20
1.3. Chemical Structure and Reactivity	22
1.4. Chemical Reactions and Photoprocesses	25
1.5. Chemical Lifetimes	26
1.6. Chemical Units	27
1.7. Summary	27
1.8. Problems	27
<b>2 The Sun, the Earth, and the Evolution of the Earth's Atmosphere</b>	<b>29</b>
2.1. The Sun and Its Origin	29
2.2. Spectra of the Radiation of the Sun and the Earth	31
2.3. Primordial Evolution of the Earth and Its Atmosphere	33
2.3.1. <i>Solid Earth Formation</i>	35
2.3.2. <i>Prebiotic Atmosphere</i>	36
2.3.3. <i>Biotic Atmosphere before Oxygen</i>	36
2.3.4. <i>The Oxygen Age</i>	39
2.3.5. <i>Aerobic Respiration and the Oxygen Cycle</i>	41
2.3.6. <i>The Nitrogen Cycle</i>	41
2.3.7. <i>Summary of Atmospheric Evolution</i>	42
2.4. Summary	43
2.5. Problems	43

<b>3</b>	<b>Structure and Composition of the Present-Day Atmosphere</b>	<b>45</b>
3.1.	Air Pressure and Density Structure	45
3.2.	Processes Affecting Temperature	46
3.2.1.	<i>Conduction</i>	47
3.2.2.	<i>Convection</i>	48
3.2.3.	<i>Advection</i>	48
3.2.4.	<i>Radiation</i>	48
3.3.	Temperature Structure of the Atmosphere	49
3.3.1.	<i>Troposphere</i>	49
3.3.2.	<i>Stratosphere</i>	51
3.3.3.	<i>Mesosphere</i>	51
3.3.4.	<i>Thermosphere</i>	52
3.4.	Equation of State	52
3.5.	Composition of the Present-Day Atmosphere	55
3.5.1.	<i>Well-Mixed Gases</i>	55
3.5.2.	<i>Spatially and Temporally Varying Gases</i>	56
3.6.	Characteristics of Selected Gases and Aerosol Particle Components	56
3.6.1.	<i>Water Vapor</i>	56
3.6.2.	<i>Carbon Dioxide</i>	58
3.6.3.	<i>Carbon Monoxide</i>	63
3.6.4.	<i>Methane</i>	64
3.6.5.	<i>Ozone</i>	65
3.6.6.	<i>Sulfur Dioxide</i>	66
3.6.7.	<i>Nitric Oxide</i>	66
3.6.8.	<i>Nitrogen Dioxide</i>	67
3.6.9.	<i>Lead</i>	68
3.6.10.	<i>Hazardous Organic Compounds</i>	70
3.7.	Summary	71
3.8.	Problems	71
<b>4</b>	<b>Urban Air Pollution</b>	<b>73</b>
4.1.	History and Early Regulation of Outdoor Urban Air Pollution	73
4.1.1.	<i>Before 1200: Metal Smelting and Wood Burning</i>	73
4.1.2.	<i>1200–1700: Quicklime Production and Coal Burning</i>	74
4.1.3.	<i>1700–1840: The Steam Engine</i>	74
4.1.4.	<i>Regulation in the United Kingdom: 1840–1930</i>	77
4.1.5.	<i>Regulation in the United States: 1869–1940</i>	77
4.1.6.	<i>London-Type Smog</i>	77
4.1.7.	<i>Photochemical Smog</i>	80
4.2.	Gas-Phase Chemistry of the Background Troposphere	85
4.2.1.	<i>Photostationary-State Ozone Concentration</i>	85
4.2.2.	<i>Daytime Removal of Nitrogen Oxides</i>	85
4.2.3.	<i>Nighttime Nitrogen Chemistry</i>	86
4.2.4.	<i>Ozone Production from Carbon Monoxide</i>	86
4.2.5.	<i>Ozone Production from Methane</i>	86
4.2.6.	<i>Ozone Production from Formaldehyde</i>	87
4.2.7.	<i>Ozone Production from Ethane</i>	87
4.2.8.	<i>Ozone and Peroxyacetyl Nitrate Production from Acetaldehyde</i>	88
4.3.	Chemistry of Photochemical Smog	88
4.3.1.	<i>Emissions of Photochemical Smog Precursors</i>	89
4.3.2.	<i>Reactive Organic Gas Breakdown Processes</i>	91

4.3.3. <i>Ozone Production from Alkanes</i>	92
4.3.4. <i>Ozone Production from Alkenes</i>	92
4.3.5. <i>Ozone Production from Aromatics</i>	93
4.3.6. <i>Ozone Production from Terpenes</i>	94
4.3.7. <i>Ozone Production from Alcohols</i>	95
4.3.8. <i>Ethanol versus Gasoline Effects on Air Pollution and Health</i>	97
4.4. Pollutant Removal	98
4.5. Summary	98
4.6. Problems	99
<b>5 Aerosol Particles in the Polluted and Global Atmosphere</b>	<b>101</b>
5.1. Size Distributions	101
5.2. Sources and Compositions of New Particles	103
5.2.1. <i>Emissions</i>	103
5.2.2. <i>Homogeneous Nucleation</i>	111
5.3. Processes Affecting Particle Size	112
5.3.1. <i>Coagulation</i>	112
5.3.2. <i>Growth Processes</i>	113
5.3.3. <i>Removal Processes</i>	119
5.4. Summary of the Composition of Aerosol Particles	120
5.5. Aerosol Particle Morphology and Shape	120
5.6. Health Effects of Aerosol Particles	122
5.7. Quantifying the Health Effects of Particles or Gases	123
5.8. Summary	124
5.9. Problems	124
<b>6 Effects of Meteorology on Air Pollution</b>	<b>127</b>
6.1. Forces	127
6.1.1. <i>Pressure Gradient Force</i>	127
6.1.2. <i>Apparent Coriolis Force</i>	127
6.1.3. <i>Friction Force</i>	128
6.1.4. <i>Apparent Centrifugal Force</i>	128
6.2. Winds	128
6.2.1. <i>Geostrophic Wind</i>	128
6.2.2. <i>Surface Winds along Straight Isobars</i>	129
6.2.3. <i>Gradient Wind</i>	129
6.2.4. <i>Surface Winds along Curved Isobars</i>	130
6.3. Global Circulation of the Atmosphere	131
6.3.1. <i>Equatorial Low-Pressure Belt</i>	132
6.3.2. <i>Winds Aloft in the Hadley Cells</i>	132
6.3.3. <i>Subtropical High-Pressure Belts</i>	132
6.3.4. <i>Trade Winds</i>	133
6.3.5. <i>Subpolar Low-Pressure Belts</i>	133
6.3.6. <i>Westerly Winds Aloft at Midlatitudes</i>	133
6.3.7. <i>Polar Easterlies</i>	134
6.4. Semipermanent Pressure Systems	134
6.5. Thermal Pressure Systems	135
6.6. Effects of Large-Scale Pressure Systems on Air Pollution	135
6.6.1. <i>Vertical Pollutant Transport</i>	136
6.6.2. <i>Horizontal Pollutant Transport</i>	142
6.6.3. <i>Cloud Cover</i>	144

6.7. Effects of Local Meteorology on Air Pollution	144
6.7.1. <i>Ground Temperatures</i>	144
6.7.2. <i>Soil Liquid Water Content</i>	145
6.7.3. <i>Urban Heat Island Effect</i>	145
6.7.4. <i>Local Winds</i>	145
6.7.5. <i>Plume Dispersion</i>	150
6.8. Summary	150
6.9. Problems	151
<b>7 Effects of Pollution on Visibility, Ultraviolet Radiation, and Colors in the Sky</b>	<b>153</b>
7.1. Processes Affecting Solar Radiation in the Atmosphere	153
7.1.1. <i>Gas Absorption</i>	154
7.1.2. <i>Gas Scattering</i>	156
7.1.3. <i>Aerosol and Hydrometeor Particle Absorption</i>	158
7.1.4. <i>Aerosol and Hydrometeor Particle Scattering</i>	162
7.1.5. <i>Particle Scattering and Absorption Extinction Coefficients</i>	165
7.2. Visibility	166
7.3. Colors in the Atmosphere	170
7.3.1. <i>White Hazes and Clouds</i>	170
7.3.2. <i>Reddish and Brown Colors in Smog</i>	170
7.3.3. <i>Black Colors in Smog</i>	172
7.3.4. <i>Red Skies and Brilliant Horizons in Smog</i>	172
7.3.5. <i>Purple Glow in the Stratosphere</i>	172
7.4. Summary	172
7.5. Problems	173
7.6. Visibility Project	174
<b>8 International Regulation of Urban Smog Since the 1940s</b>	<b>175</b>
8.1. Regulation in the United States	175
8.1.1. <i>Air Pollution Control Act of 1955</i>	175
8.1.2. <i>California Vehicle Emission Regulations</i>	176
8.1.3. <i>Clean Air Act of 1963</i>	176
8.1.4. <i>Motor Vehicle Air Pollution Control Act of 1965</i>	176
8.1.5. <i>Air Quality Act of 1967</i>	178
8.1.6. <i>Clean Air Act Amendments of 1970</i>	178
8.1.7. <i>Catalytic Converters</i>	180
8.1.8. <i>Corporate Average Fuel Economy Standards</i>	181
8.1.9. <i>Clean Air Act Amendments of 1977</i>	181
8.1.10. <i>Clean Air Act Amendments of 1990</i>	182
8.1.11. <i>Clean Air Act Revision of 1997</i>	183
8.1.12. <i>California Waiver</i>	183
8.1.13. <i>Regulation of U.S. Interstate and Transboundary Air Pollution</i>	184
8.1.14. <i>Smog Alerts</i>	185
8.1.15. <i>U.S. Air Quality Trends from the 1970s to Present</i>	186
8.1.16. <i>Visibility Regulations and Trends</i>	188
8.2. Pollution Trends and Regulations outside the United States	189
8.2.1. <i>European Union</i>	190
8.2.2. <i>United Kingdom</i>	191
8.2.3. <i>France</i>	192
8.2.4. <i>Germany</i>	192
8.2.5. <i>Russia</i>	193

8.2.6. <i>Israel</i>	195
8.2.7. <i>Egypt</i>	196
8.2.8. <i>Iran</i>	196
8.2.9. <i>India</i>	196
8.2.10. <i>China</i>	197
8.2.11. <i>Japan</i>	199
8.2.12. <i>Canada</i>	200
8.2.13. <i>Mexico</i>	201
8.2.14. <i>Brazil</i>	202
8.2.15. <i>Chile</i>	202
8.2.16. <i>South Africa</i>	203
8.2.17. <i>Australia</i>	204
8.3. Summary	205
8.4. Problems	205
<b>9 Indoor Air Pollution</b>	<b>207</b>
9.1. Pollutants in Indoor Air and Their Sources	207
9.1.1. <i>Carbon Dioxide</i>	207
9.1.2. <i>Carbon Monoxide</i>	208
9.1.3. <i>Nitrogen Dioxide</i>	208
9.1.4. <i>Ozone</i>	208
9.1.5. <i>Sulfur Dioxide</i>	209
9.1.6. <i>Formaldehyde</i>	209
9.1.7. <i>Radon</i>	209
9.1.8. <i>Volatile Organic Compounds</i>	211
9.1.9. <i>Allergens</i>	211
9.1.10. <i>Coal Dust</i>	212
9.1.11. <i>Asbestos</i>	212
9.1.12. <i>Fungal Spores, Bacteria, Viruses, and Pollen</i>	214
9.1.13. <i>Environmental Tobacco Smoke</i>	214
9.1.14. <i>Indoor Solid Biofuel and Coal Burning</i>	217
9.2. Sick Building Syndrome	217
9.3. Personal Clouds	218
9.4. Regulation of Indoor Air Pollution	218
9.5. Summary	219
9.6. Problems	219
<b>10 Acid Deposition</b>	<b>221</b>
10.1. Historical Aspects of Acid Deposition	221
10.2. Causes of Acidity	224
10.2.1. <i>Carbonic Acid</i>	225
10.2.2. <i>Sulfuric Acid</i>	225
10.2.3. <i>Nitric Acid</i>	226
10.2.4. <i>Hydrochloric Acid</i>	226
10.2.5. <i>Natural and Anthropogenic Sources of Acids</i>	226
10.2.6. <i>Acidity of Rainwater and Fog Water</i>	226
10.3. Sulfuric Acid Deposition	226
10.3.1. <i>Gas-Phase Oxidation of S(IV)</i>	227
10.3.2. <i>Aqueous-Phase Oxidation of S(IV)</i>	227
10.4. Nitric Acid Deposition	228

10.5.	Effects of Acid Deposition	228
	10.5.1. <i>Effects on Lakes and Streams</i>	228
	10.5.2. <i>Effects on Biomass</i>	228
	10.5.3. <i>Effects on Buildings and Sculptures</i>	231
10.6.	Natural and Artificial Neutralization of Lakes and Soils	231
	10.6.1. <i>Ammonium Hydroxide</i>	231
	10.6.2. <i>Sodium and Calcium Hydroxide</i>	231
	10.6.3. <i>Calcium Carbonate</i>	232
	10.6.4. <i>Sodium Chloride</i>	233
	10.6.5. <i>Ammonia</i>	233
10.7.	Recent Regulatory Control of Acid Deposition	234
	10.7.1. <i>Methods of Controlling Emissions</i>	234
	10.7.2. <i>Effects of Regulation</i>	235
10.8.	Summary	235
10.9.	Problems	236
<b>11</b>	<b>Global Stratospheric Ozone Reduction</b>	<b>237</b>
11.1.	Structure of the Present-Day Ozone Layer	237
11.2.	Relationship between the Ozone Layer and Ultraviolet Radiation	239
11.3.	Chemistry of the Natural Ozone Layer	240
	11.3.1. <i>The Chapman Cycle</i>	240
	11.3.2. <i>Effects of Nitrogen on the Natural Ozone Layer</i>	242
	11.3.3. <i>Effects of Hydrogen on the Natural Ozone Layer</i>	243
	11.3.4. <i>Effects of Carbon on the Natural Ozone Layer</i>	243
11.4.	Recent Changes to the Ozone Layer	243
	11.4.1. <i>Global Stratospheric Changes</i>	243
	11.4.2. <i>Antarctic Stratospheric Changes</i>	244
	11.4.3. <i>Arctic Stratospheric Changes</i>	244
	11.4.4. <i>Effects of Ozone and Air Pollution Changes on Ultraviolet Radiation</i>	245
11.5.	Effects of Chlorine on Global Ozone Reduction	245
	11.5.1. <i>Chlorofluorocarbons and Related Compounds</i>	246
	11.5.2. <i>Lifetimes and Mixing Ratios of Chlorinated Compounds</i>	249
	11.5.3. <i>Catalytic Ozone Destruction by Chlorine</i>	250
11.6.	Effects of Bromine on Global Ozone Reduction	251
11.7.	Regeneration Rates of Stratospheric Ozone	251
11.8.	Antarctic Ozone Hole	252
	11.8.1. <i>Polar Stratospheric Cloud Formation</i>	253
	11.8.2. <i>Polar Stratospheric Cloud Surface Reactions</i>	254
	11.8.3. <i>Springtime Polar Chemistry</i>	255
11.9.	Effects of Enhanced UV-B Radiation on Life and Ecosystems	256
	11.9.1. <i>Effects on Humans</i>	256
	11.9.2. <i>Effects on Microorganisms, Animals, and Plants</i>	258
	11.9.3. <i>Effects on the Global Carbon and Nitrogen Cycles</i>	258
	11.9.4. <i>Effects on Tropospheric Ozone</i>	258
11.10.	Regulation of Chlorofluorocarbons	259
11.11.	Summary	261
11.12.	Problems	261
<b>12</b>	<b>The Greenhouse Effect and Global Warming</b>	<b>263</b>
12.1.	Temperature on Earth in the Absence of a Greenhouse Effect	263
	12.1.1. <i>Incoming Solar Radiation</i>	264



12.1.2. <i>Outgoing Thermal-Infrared Radiation</i>	266
12.1.3. <i>Equilibrium Temperature of the Earth</i>	266
12.1.4. <i>The Goldilocks Hypothesis</i>	268
12.2. <i>The Greenhouse Effect and Global Warming</i>	268
12.2.1. <i>Greenhouse Gases and Particles</i>	268
12.2.2. <i>Historical Aspects of Global Warming</i>	270
12.2.3. <i>Leading Causes of Global Warming</i>	270
12.2.4. <i>Trends in Mixing Ratios and Emissions of Gases and Particles</i>	272
12.3. <i>Recent and Historical Temperature Trends</i>	274
12.3.1. <i>Recent Temperature Record</i>	274
12.3.2. <i>Historical Temperature Record</i>	276
12.4. <i>Feedbacks and Other Factors That May Affect Global Temperatures</i>	288
12.4.1. <i>Arguments Mistakenly Used to Explain Global Warming as a Natural Phenomenon</i>	288
12.4.2. <i>Feedback of Gases to Climate</i>	289
12.4.3. <i>Effects of Aerosol Particles on Climate</i>	290
12.5. <i>Consequences of Global Warming</i>	294
12.5.1. <i>Loss of Ice/Rise in Sea Level</i>	295
12.5.2. <i>Changes in Regional Climate, Severe Weather, and Agriculture</i>	296
12.5.3. <i>Changes in Ocean Acidity and Ecosystems</i>	297
12.5.4. <i>Changes in Heat Stress</i>	297
12.5.5. <i>Changes in Disease</i>	298
12.5.6. <i>Changes in Air Pollution</i>	298
12.5.7. <i>Changes in Stratospheric Ozone</i>	300
12.6. <i>Regulatory Control of Global Warming</i>	301
12.6.1. <i>Indirect Regulations</i>	301
12.6.2. <i>The Kyoto Protocol</i>	302
12.6.3. <i>Renewable Portfolio Standards and the California Waiver</i>	304
12.6.4. <i>Fastest Methods of Slowing Global Warming</i>	304
12.7. <i>Summary</i>	306
12.8. <i>Problems</i>	307
12.9. <i>Essay Questions</i>	307

### **13 Energy Solutions to Air Pollution and Global Warming 309**

13.1. <i>Clean, Low-Risk, Sustainable Energy Systems</i>	309
13.1.1. <i>Why Not Nuclear Energy?</i>	310
13.1.2. <i>Why Not Coal with Carbon Capture?</i>	312
13.1.3. <i>Why Not Natural Gas?</i>	313
13.1.4. <i>Why Not Liquid or Solid Biofuels?</i>	314
13.1.5. <i>Demand-Side Energy Conservation</i>	315
13.2. <i>Characteristics of Electricity-Generating Wind, Water, and Sunlight Technologies</i>	317
13.2.1. <i>Wind</i>	317
13.2.2. <i>Wave</i>	318
13.2.3. <i>Geothermal</i>	318
13.2.4. <i>Hydroelectric</i>	319
13.2.5. <i>Tidal</i>	320
13.2.6. <i>Solar Photovoltaics</i>	320
13.2.7. <i>Concentrated Solar Power</i>	320
13.2.8. <i>Use of Wind, Water, and Sunlight Power for Transportation</i>	321
13.2.9. <i>Use of Wind, Water, and Sunlight Power for Heating and Cooling</i>	322
13.3. <i>Energy Needed to Power the World</i>	323