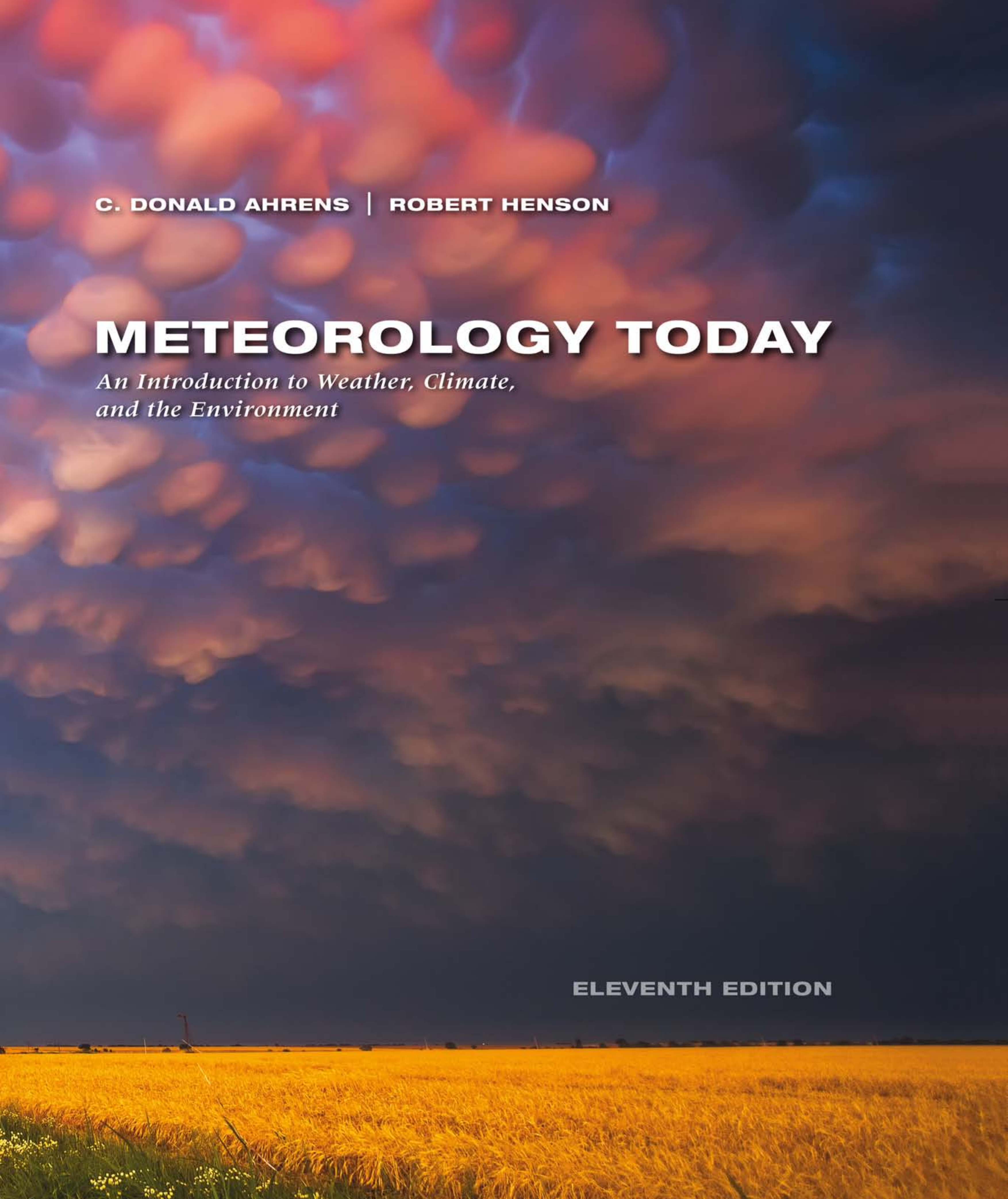

C. DONALD AHRENS | ROBERT HENSON

METEOROLOGY TODAY

An Introduction to Weather, Climate, and the Environment

ELEVENTH EDITION

ELEVENTH EDITION

METEOROLOGY TODAY

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Meteorology Today

AN INTRODUCTION TO WEATHER, CLIMATE, AND THE ENVIRONMENT

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Meteorology Today:
An Introduction to Weather, Climate, and the Environment,
Eleventh Edition
C. Donald Ahrens, Robert Henson

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Cover Image: © extremeinstability.com
Compositor: Graphic World, Inc.

Library of Congress Control Number 2014952597

Student Edition:
ISBN-13: 978-1-305-11358-9
ISBN-10: 1-305-11358-6

Loose-leaf Edition:
ISBN-13: 978-1-305-26500-4
ISBN-10: 1-305-26500-9

Cengage Learning
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Printed in Canada

Print Number: 01 Print Year: 2014

CONTENTS IN BRIEF

CONTENTS

CHAPTER 1

CHAPTER 2

© C. Donald Ahrens

CHAPTER 3

Seasonal and Daily Temperatures 59

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CHAPTER 4

Atmospheric Humidity 93

CHAPTER 5

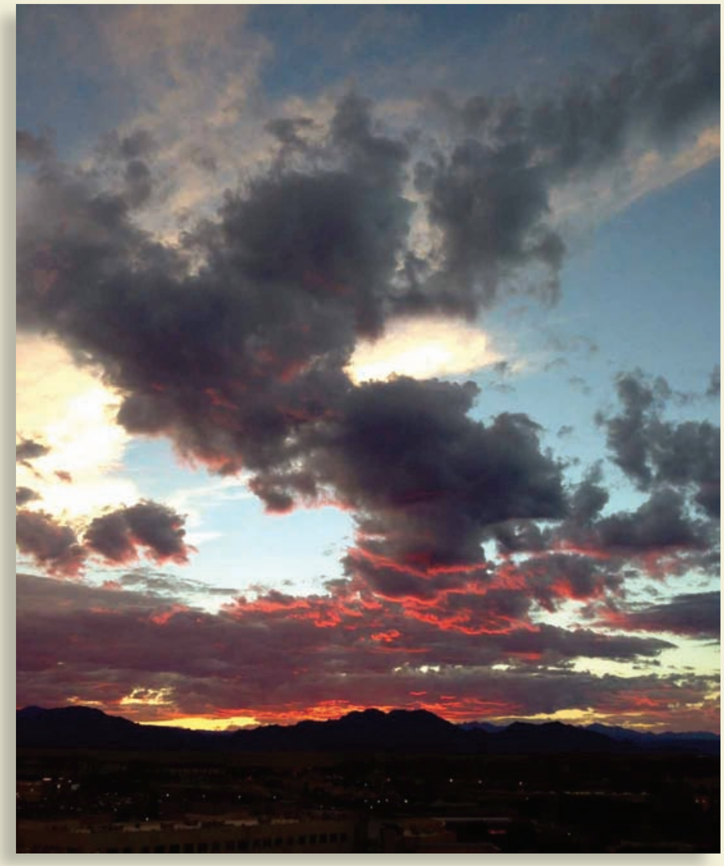
Condensation: Dew, Fog, and Clouds 115

CHAPTER 6

Stability and Cloud Development 145

CHAPTER 7

Precipitation 169



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CHAPTER 8

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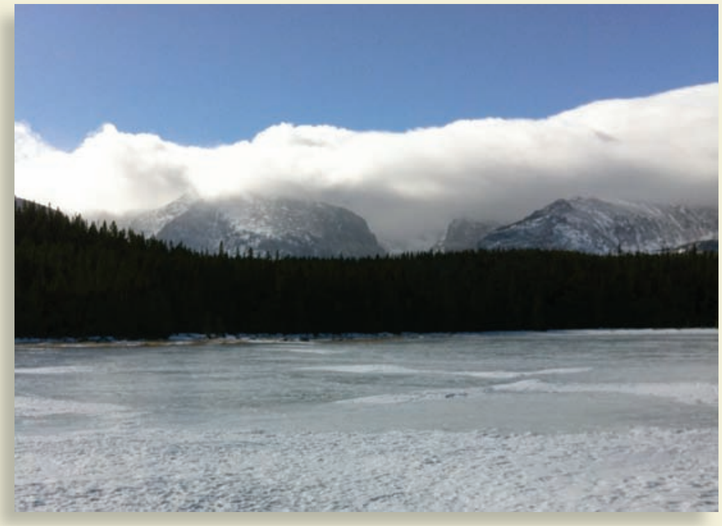
CHAPTER 9

CHAPTER 10

CHAPTER 11



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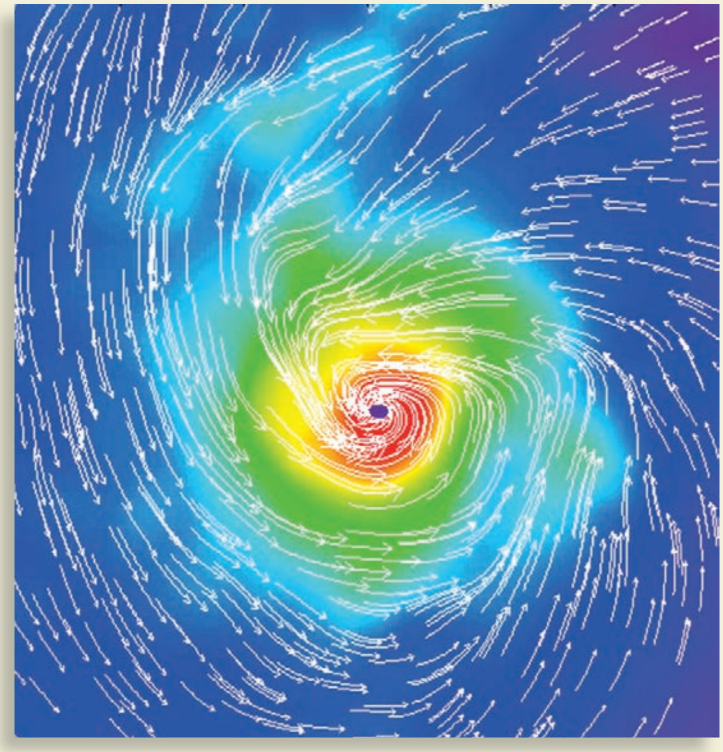
CHAPTER 12



NASA

CHAPTER 13

© Robert Henson

CHAPTER 14

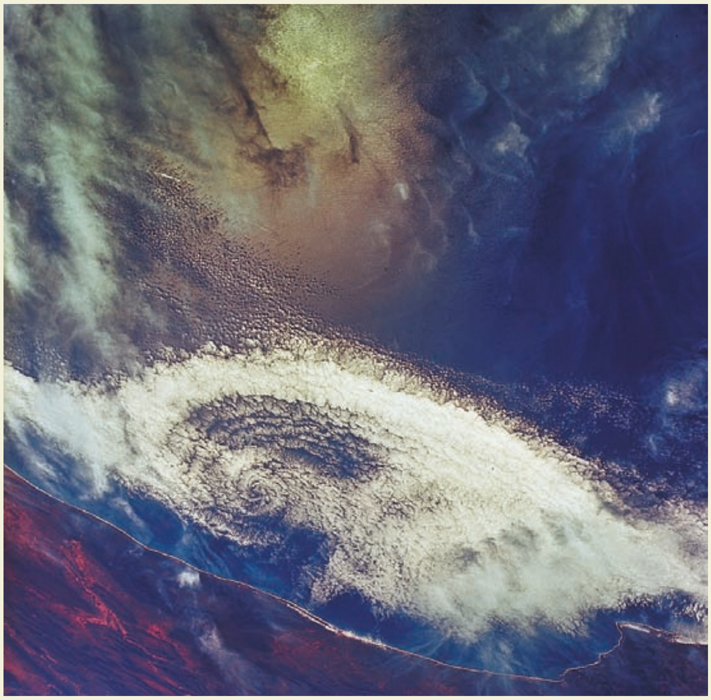
Thunderstorms 383

CHAPTER 15

Tornadoes 415

CHAPTER 16

Hurricanes 439


NASA

CHAPTER 17

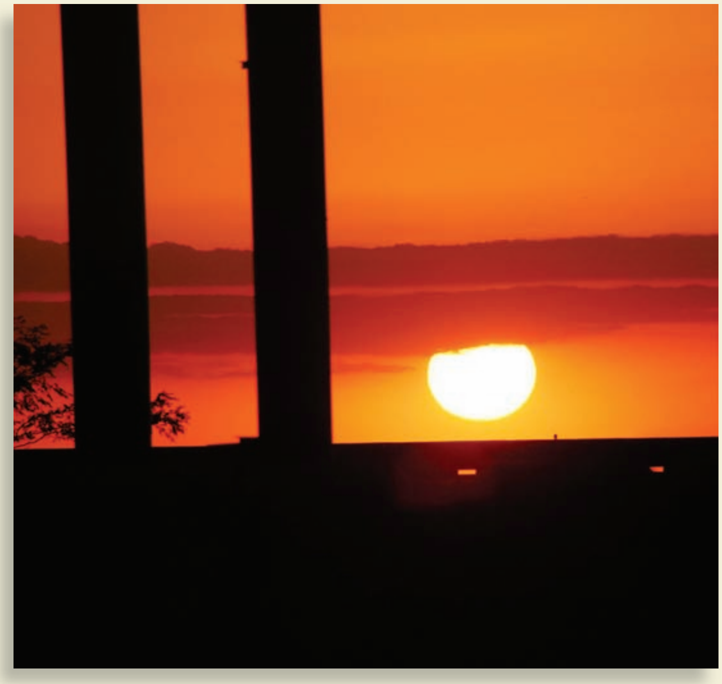
Global Climate 471

CHAPTER 18

Earth's Changing Climate 501

CHAPTER 19

Air Pollution 535



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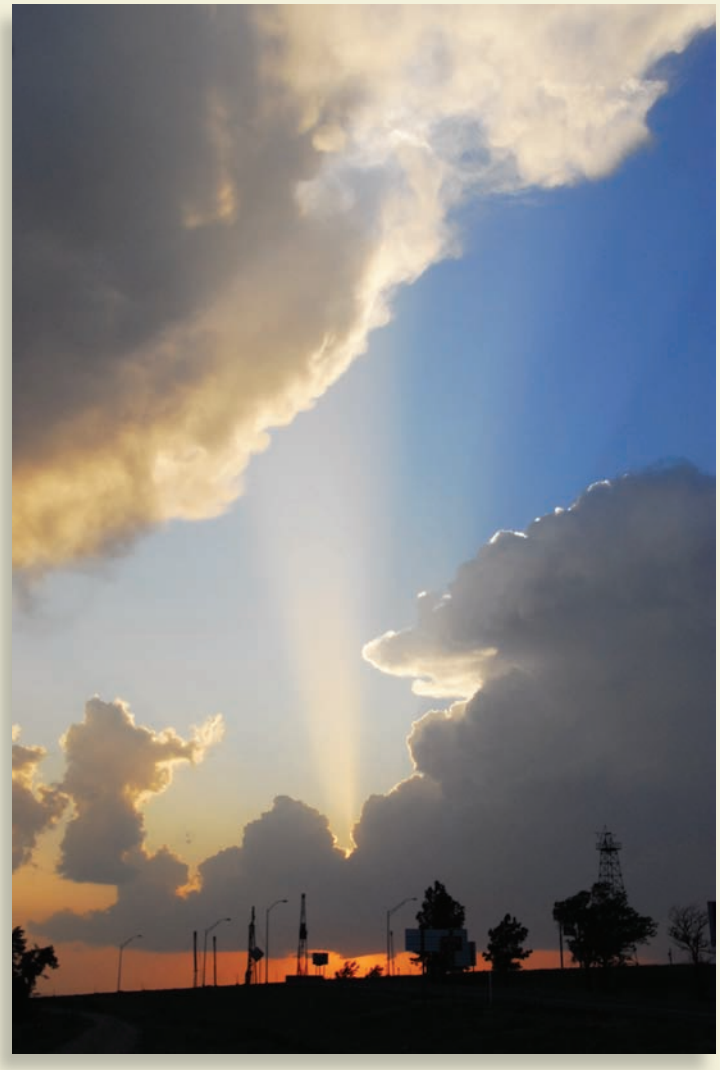

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PREFACE

The world is an ever-changing picture of naturally occurring events. From drought and famine to devastating floods, some of the greatest challenges we face come in the form of natural disasters created by weather. Yet dealing with weather and climate is an inevitable part of our lives. Sometimes it is as small as deciding what to wear for the day or how to plan a vacation. But it can also have life-shattering consequences, especially for those who are victims of a hurricane or a tornado.

Weather has always been front-page news, but in recent years, extreme weather seems to receive an ever-increasing amount of coverage. From the record-setting tornadoes of 2011 to widespread drought in 2012 and the devastation wrought by Hurricane/Superstorm Sandy late that year, weather has enormous impact on our lives. The longer-term challenges of an evolving climate also demand our attention, whether it be rising sea levels, near-record global temperatures, intensified downpours, or the retreat of Arctic sea ice. Thanks in part to the rise of social media, more people than ever are sharing their weather-related observations, impressions, and photographs with the world at large. For these and many other reasons, interest in meteorology (the study of the atmosphere) continues to grow. One of the reasons that meteorology is such an engaging science to study is that the atmosphere is a universally accessible laboratory for everyone. Although the atmosphere will always provide challenges for us, as research and technology advance, our ability to understand and predict our atmosphere improves as well. We hope this book serves to assist you as you develop your own personal understanding and appreciation of our planet's dynamic, spectacular atmosphere.

About This Book

Meteorology Today is written for college-level students taking an introductory course on the atmospheric environment. As was the case in previous editions, no special prerequisites are necessary. The main purpose of the text is to convey meteorological concepts in a visual and practical manner, while simultaneously providing students with a comprehensive background in basic meteorology. This eleventh edition includes up-to-date information on important topics, including climate change, ozone depletion, and El Niño. Also included are discussions of high-profile weather events, such as droughts, heat waves, tornado outbreaks, and hurricanes of recent years.

Written expressly for the student, this book emphasizes the understanding and application of meteorological principles. The text encourages watching the weather so that it becomes "alive," allowing readers to immediately apply textbook material to the world around them. To assist with this endeavor, a color Cloud Chart appears at the end of this text. The Cloud Chart can be separated from the book and used as a learning tool any place where one chooses to observe the sky. Numerous full-color illustrations and photographs illustrate key features of the atmosphere, stimulate interest, and show how exciting the study of weather can be.

After an introductory chapter on the composition, origin, and structure of the atmosphere, the book covers energy, temperature, moisture, precipitation, and winds. Next come chapters that deal with air masses and middle-latitude cyclones, followed by weather prediction and severe storms, including a newly separated and enlarged chapter devoted to tornadoes. Wrapping up the book are chapters on hurricanes, global climate, climate change, air pollution, and atmospheric optics.

This book is structured to provide maximum flexibility to instructors of atmospheric science courses, with chapters generally designed so that they can be covered in any desired order. For example, the chapter on atmospheric optics, Chapter 20, is self-contained and can be covered before or after any chapter. Instructors, then, are able to tailor this text to their particular needs.

Each chapter contains at least two Focus sections, which expand on material in the main text or explore a subject closely related to what is being discussed. Focus sections fall into one of five distinct categories: Observations, Special Topics, Environmental Issues, Advanced Topics, and Social and Economic Impacts. Some include material that is not always found in introductory meteorology textbooks, such as temperature extremes, cloud seeding, and the weather on other planets. Others help to bridge theory and practice. Focus sections new to this edition include "The Challenge of Predicting El Niño and La Niña" (Chapter 10), "The Forecast Funnel" and "The Forecast in Words and Pictures" (Chapter 13), "The Evolution of Tornado Watches and Warnings" (Chapter 15), and "Are Plant Hardiness Zones Shifting Northward?" (Chapter 17). Quantitative discussions of important equations, such as the geostrophic wind equation and the hydrostatic equation, are found in Focus sections on advanced topics.

Set apart as "Weather Watch" features in each chapter is weather information that may not be commonly known, yet pertains to the topic under discussion. Designed to bring the reader into the text, most of these weather highlights relate to some interesting weather fact or astonishing event.

Each chapter incorporates other effective learning aids:

- A major topic outline begins each chapter.
- Interesting introductory pieces draw the reader naturally into the main text.
- Important terms are boldfaced, with their definitions appearing in the glossary or in the text.
- Key phrases are italicized.
- English equivalents of metric units in most cases are immediately provided in parentheses.

- A brief review of the main points is placed toward the middle of most chapters.
- Each chapter ends with a summary of the main ideas.
- A list of key terms with page references follows each chapter, allowing students to review and reinforce their knowledge of key concepts.
- Questions for Review act to check how well students assimilate the material.
- Questions for Thought require students to synthesize learned concepts for deeper understanding.
- Problems and Exercises require mathematical calculations that provide a technical challenge to the student.
- References to more than 15 Concept Animations are spread throughout the chapters. These animations (several of which are new) convey an immediate appreciation of how a process works and help students visualize the more difficult concepts in meteorology. Animations can be found in MindTap, accessed through CengageBrain.com.
- At the end of each chapter are questions that relate to articles found on the Global Geoscience Watch website available on its own or via MindTap.

Three appendices conclude the book. In addition, at the end of the book, a compilation of supplementary reading material is presented, as is an extensive glossary.

New to this edition are Online Appendices that allow students access to a wide variety of supplemental material, including tools for weather prediction and background on watches, warnings, and advisories.

On the endsheet at the back of the book is a geophysical map of North America. The map serves as a quick reference for locating states, provinces, and geographical features, such as mountain ranges and large bodies of water.

Supplemental Material and Technology Support

TECHNOLOGY FOR THE INSTRUCTOR Cognero Test Bank/Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to:

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Global Geoscience Watch Updated several times a day, the Global Geoscience Watch is an ideal one-stop site for classroom discussion and research projects for all things geoscience. Broken into the four key course areas (Geography, Geology, Meteorology, and Oceanography), you can easily get to the most relevant content available for your course. You and your students will have access to the latest information from trusted academic journals, news outlets, and magazines. You also will receive access to statistics, primary sources, case studies, podcasts, and much more.

TECHNOLOGY FOR THE STUDENT MindTap Meteorology is a new approach to highly personalized online learning. Beyond an eBook, homework solution, digital supplement, or premium website, MindTap is a digital learning platform that works alongside your campus LMS to deliver course curriculum across the range of electronic devices in your life. MindTap is built on an "app" model allowing enhanced digital collaboration and delivery of engaging content across a spectrum of Cengage and non-Cengage resources.

A Workbook/Study Guide written by Don Ahrens, first author of this book, reinforces concepts learned in *Meteorology Today,* Eleventh Edition. Each chapter contains a summary of the text, a list of important concepts, self-tests with answers (which include multiple choice, true/false, matching, short answer, and/or fill in the blank), and a list of additional readings.

Changes in the Eleventh Edition

This edition of *Meteorology Today* includes a coauthor—meteorologist and science journalist Robert Henson. For more than 20 years, Henson has produced publications and websites for the University Corporation for Atmospheric Research, which manages the National Center for Atmospheric Research. He is an expert on severe weather, including tornadoes, thunderstorms, and hurricanes. He has also analyzed how television weathercasters cover major storms and report on climate change. Henson is the author of four trade books on meteorology, including *The Thinking Person's Guide to Climate Change* (previously *The Rough Guide to Climate Change*, whose first edition was shortlisted for the United Kingdom's Royal Society Prize for Science Books).

The authors have carried out extensive updates and revisions to this eleventh edition of *Meteorology Today,* reflecting the ever-changing nature of the field and the atmosphere itself. More than 65 new or revised color illustrations and more than 45 new photos have been added to help visualize the excitement of the atmosphere.

- Chapter 1, "Earth and Its Atmosphere," continues to serve as a broad overview of the atmosphere. Material that puts meteorology in the context of the scientific method is now presented in the text, laying the foundation for the rest of the book.
- Chapter 2, "Energy: Warming Earth and the Atmosphere," includes updated information on greenhouse gases and their influence on global warming, a topic covered in more detail later in the book. The discussion of space weather now appears in a Focus section.
- Chapter 3, "Seasonal and Daily Temperatures," has been restructured so that the material on extreme high and low temperatures is now included in the main narrative.
- Chapter 4, "Atmospheric Humidity," continues to convey important concepts related to how humidity is expressed and atmospheric moisture content is measured.
- Chapter 5, "Condensation: Dew, Fog, and Clouds," spotlights one of the most recently recognized cloud types (asperatus undulatus) and features updated information on satellites, including the Global Precipitation Measurement (GPM) mission.
- Chapter 6, "Stability and Cloud Development," discusses atmospheric stability and instability and the resulting effects on cloud formation in a carefully sequenced manner, with numerous illustrations and several Focus sections helping to make these complex concepts understandable.
- "Precipitation" (Chapter 7) includes coverage of the high-impact Atlanta snowstorm of 2014 and other recent snow and ice events, as well as expanded discussion of snow measurement techniques.
- Chapter 8, "Air Pressure and Winds," includes a substantially enhanced description and revised illustrations of the interplay between the pressure gradient and Coriolis forces in cyclonic and anticylonic flow. Several other illustrations have been revised for clarity.
- Chapter 9, "Wind: Small-Scale and Local Systems," includes several revised illustrations and a number of other updates, including new discussion of such observing systems as sonic anemometers and dropsondes. The Focus section on wind energy has also been updated.
- Chapter 10, "Wind: Global Systems," features a major restructuring, update, and expansion of sections dealing with the El Niño/Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, and Arctic Oscillation. A new Focus section explains how El Niño and La Niña forecasts are produced.
- In Chapter 11, "Air Masses and Fronts," the concept of atmospheric rivers is now introduced, and a number of illustrations have been revised for clarity.
- With minor revisions, Chapter 12, "Middle Latitude Cyclones," continues to provide a thorough and accessible introduction to this important topic.
- Chapter 13, "Weather Forecasting," has undergone a major revision. Two new Focus sections introduce the student to the forecast-funnel concept and the ways in which forecasts are communicated verbally and pictorially. The narrative has been restructured so that the student moves from traditional types of weather forecasting to numerical weather prediction. In addition, an exercise that takes students through the forecasting process now incorporates forecast-funnel concepts.
- Due to strong interest among students, and at the suggestion of a number of reviewers, the previous single chapter on thunderstorms and tornadoes has been expanded into two chapters, each one a manageable length. In Chapter 14, "Thunderstorms," the discussions of such topics as microbursts, heat bursts, and record hailstones have been updated, and the Washington, D.C., derecho of 2012 has been included. Both low- and high-precipitation supercells are introduced, and capping inversions are discussed at greater length. Chapter 15, "Tornadoes," includes a new Focus section on the evolution of tornado watches and warnings, as well as background on the devastating Oklahoma tornadoes of 2013. Storm chasing is discussed in the context of the VORTEX and VORTEX2 field campaigns and the tragic deaths of several storm researchers in 2013. Both Chapters 14 and 15 include a number of new photographs and illustrations, as well as references to the latest storm-observing technology, including dual-polarization and phased-array radars.
- Chapter 16, "Hurricanes," includes extensive background on Hurricane/Superstorm Sandy (2012) and Super Typhoon Haiyan (2013), as well as new illustrations depicting storm surge processes and wind-speed probabilities. Several new questions and exercises are also included.
- The order of the next two chapters has been reversed. Chapter 17, "Global Climate," continues to serve as a standalone unit on global climatology and classification schemes, with updates and revisions reflecting recent data, including the new 1981–2010 United States climate averages. This chapter now includes a new Focus section on the northward movement of United States plant zones.
- Chapter 18, "Earth's Changing Climate," has undergone extensive updating to reflect recent developments and

findings, including the Fifth Assessment Report (2013) from the Intergovernmental Panel on Climate Change. Many graphics have been added or updated.

- Chapter 19, “Air Pollution,” reflects a number of updates, including the role of airborne ammonia and particulates as well as recent progress in addressing acid rain and ozone depletion.
- The book concludes with Chapter 20, “Light, Color, and Atmospheric Optics,” which uses exciting photos and art to convey the beauty of the atmosphere.

Acknowledgments

Many people have contributed to this eleventh edition of *Meteorology Today.* A very special and most grateful thank-you goes to Don Ahrens’ wife, Lita, who indexed and proofread the entire book. Special thanks also go to Charles Preppernau for his care in rendering beautiful artwork and to Judith Chaffin for professional and conscientious proofreading.

We are indebted to Janet Alleyn who not only designed the book but, once again, took the photos, art, and manuscript and turned them into a beautiful book. We also thank Stuart Kenter for his conscientious editing. Special thanks go to all the people at Cengage Learning who worked on this edition, especially Aileen Berg, Jake Warde, and Hal Humphrey.

Thanks to our friends who provided photos and to those reviewers who offered comments and suggestions for this edition, including:

Eric Michael Aldrich, University of Missouri

Kim Drager, University of Kansas

Melissa Godeck, SUNY Oneonta

Redina L. Herman, Western Illinois University

Larry Hopper, University of Louisiana at Monroe

Steven Lazarus, Florida Institute of Technology

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Brent Skeeter, Salisbury University

Mike Smith, Front Range Community College

Kenneth Yanow, Southwestern College

To the Student

Learning about the atmosphere can be a fascinating and enjoyable experience. This book is intended to give you some insight into the workings of the atmosphere. However, for a real appreciation of your atmospheric environment, you must go outside and observe. Although mountains take millions of years to form, a cumulus cloud can develop into a raging thunderstorm in less than an hour. The atmosphere is always producing something new for us to behold. To help with your observations, a color Cloud Chart is at the back of the book for easy reference. Remove it and keep it with you. And remember, all of the concepts and ideas in this book are out there for you to discover and enjoy. Please, take the time to look.

Donald Ahrens and Robert Henson

ELEVENTH EDITION

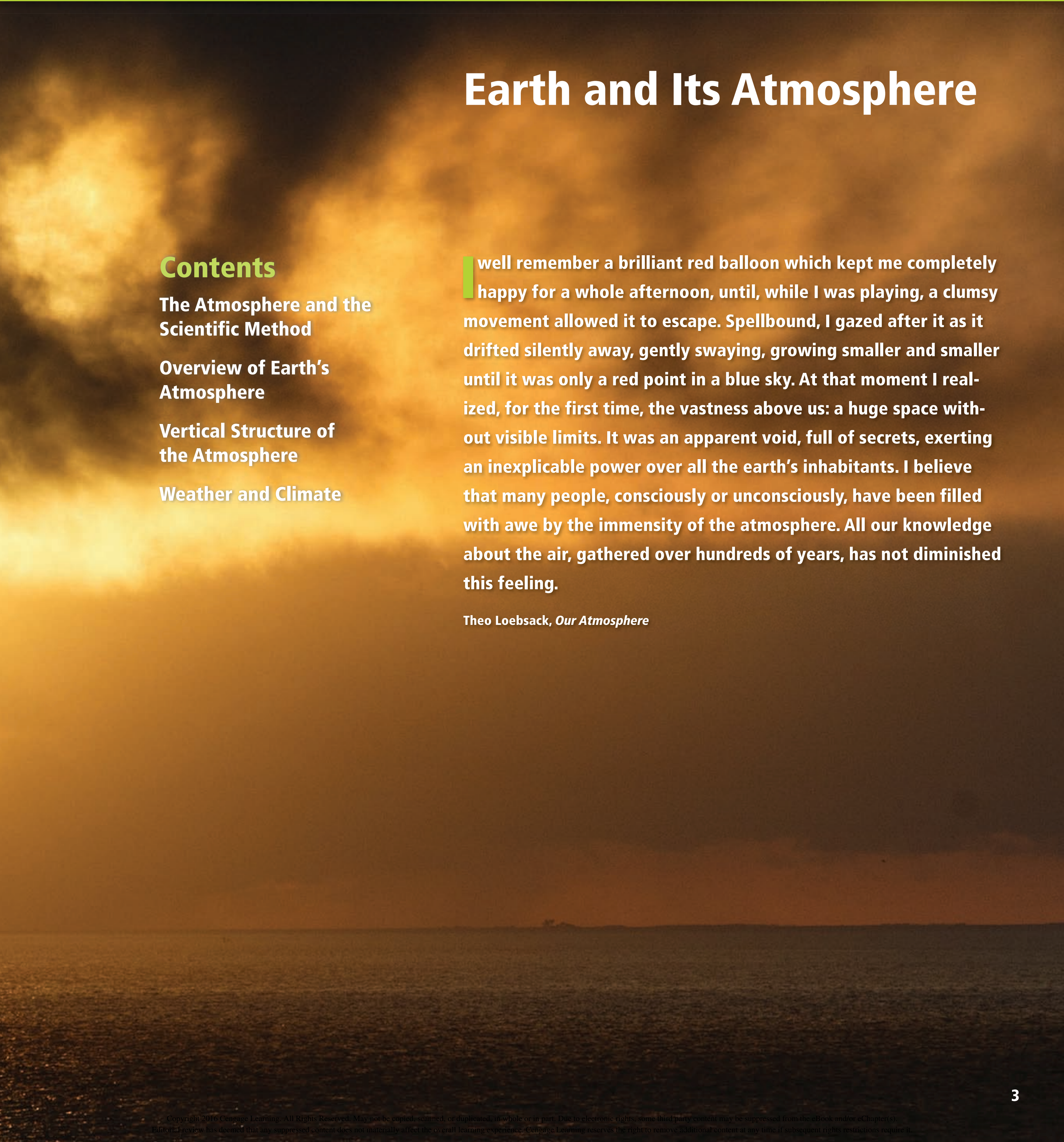
METEOROLOGY TODAY

We live at the bottom of a turbulent ocean of air where rising air can form into clouds composed of water and ice.

Tom Warner/Weather VideoHD.TV

CHAPTER 1

Earth and Its Atmosphere



Contents

> I well remember a brilliant red balloon which kept me completely happy for a whole afternoon, until, while I was playing, a clumsy movement allowed it to escape. Spellbound, I gazed after it as it drifted silently away, gently swaying, growing smaller and smaller until it was only a red point in a blue sky. At that moment I realized, for the first time, the vastness above us: a huge space without visible limits. It was an apparent void, full of secrets, exerting an inexplicable power over all the earth's inhabitants. I believe that many people, consciously or unconsciously, have been filled with awe by the immensity of the atmosphere. All our knowledge about the air, gathered over hundreds of years, has not diminished this feeling.
>
> Theo Loebsack, *Our Atmosphere*

Our **atmosphere** is a delicate life-giving blanket of air that surrounds the fragile Earth. In one way or another, it influences everything we see and hear—it is intimately connected to our lives. Air is with us from birth, and we cannot detach ourselves from its presence. In the open air, we can travel for many thousands of kilometers in any horizontal direction, but should we move a mere eight kilometers above the surface, we would suffocate. We may be able to survive without food for a few weeks, or without water for a few days, but, without our atmosphere, we would not survive more than a few minutes. Just as fish are confined to an environment of water, so we are confined to an ocean of air. Anywhere we go, air must go with us.

Earth without an atmosphere would have no lakes or oceans. There would be no sounds, no clouds, no red sunsets. The beautiful pageantry of the sky would be absent. It would be unimaginably cold at night and unbearably hot during the day. All things on Earth would be at the mercy of an intense sun beating down upon a planet utterly parched.

Living on the surface of Earth, we have adapted so completely to our environment of air that we sometimes forget how truly remarkable this substance is. Even though air is tasteless, odorless, and (most of the time) invisible, it protects us from the scorching rays of the sun and provides us with a mixture of gases that allows life to flourish. Because we cannot see, smell, or taste air, it may seem surprising that between your eyes and the pages of this book are trillions of air molecules. Some of these may have been in a cloud only yesterday, or over another continent last week, or perhaps part of the life-giving breath of a person who lived hundreds of years ago.

In this chapter, we will examine a number of important concepts and ideas about Earth's atmosphere, many of which will be expanded in subsequent chapters.

The Atmosphere and the Scientific Method

Our understanding of the atmosphere and how it produces weather is built on knowledge acquired and applied through the *scientific method*. This technique allows us to make informed predictions about how the natural world will behave. For hundreds of years, the scientific method has served as the backbone for advances in medicine, biology, engineering, and many other fields. In the field of atmospheric science, the scientific method has paved the way for the production of weather forecasts that have steadily improved over time.

Investigators use the scientific method by posing a question, putting forth a hypothesis, predicting what the hypothesis would imply if it were true, and carrying out tests to see if the prediction is accurate. Many common sayings about the weather, such as "red sky at morning, sailor take warning; red sky at night, sailor's delight," are rooted in careful observation, and there are grains of truth in some of them. However, they are not considered to be products of the scientific method because they are not tested and verified in a standard rigorous way. (See ● Fig. 1.1.)

To be accepted, a hypothesis* has to be shown to be correct through a series of quantitative tests. In many areas of science, such testing is carried out in a laboratory, where it can be replicated again and again. Studying the atmosphere, however, is somewhat different, because Earth has only one atmosphere. Despite this limitation, scientists have made vast progress by studying the physics and chemistry of air in the laboratory (for instance, the way in which molecules absorb energy) and by extending those understandings to the atmosphere as a whole. Observations using weather instruments allow us to quantify how the atmosphere behaves and to determine whether a prediction is correct. If a particular kind of weather is being studied, such as hurricanes or snowstorms, a field campaign can gather additional observations to test specific hypotheses.

Over the last 50 years, computers have given atmospheric scientists a tremendous boost. The physical laws that control atmospheric behavior can be represented in software packages known as *numerical models*. Forecasts can be made and tested many times over. The atmosphere within a model can be used to depict weather conditions from the past and project them into the future. When a model can accurately simulate past weather conditions and provide confidence in its portrayal of tomorrow's weather, the model can provide valuable information about the weather and climate we may expect decades from now.

Overview of Earth's Atmosphere

The scientific method has not only illuminated our understanding of weather and climate but also provided much information about the universe that surrounds us. The universe contains billions of galaxies and each galaxy is made up of billions of stars. Stars are hot glowing balls of gas that generate energy by converting hydrogen into helium near their centers. Our sun is an average-sized star

© UCAR, Photo by Carlye Calvin

● **FIGURE 1.1** Observing the natural world is a critical part of the scientific method. Here a vibrant red sky is visible at sunset. One might use the scientific method to verify the old proverb, "Red sky at morning, sailors take warning; red sky at night, sailor's delight."

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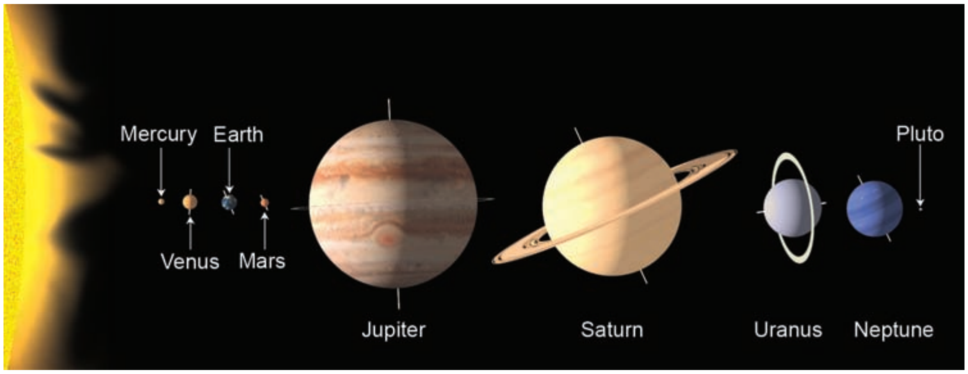
*A hypothesis is an assertion that is subject to verification of proof.



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● **FIGURE 1.2** The relative sizes and positions of the planets in our solar system. Pluto is included as an object called a *dwarf planet.* (Positions are not to scale.)

situated near the edge of the Milky Way galaxy. Revolving around the sun are Earth and seven other planets (see ● Fig. 1.2).[*] These planets, along with a host of other material (comets, asteroids, meteors, dwarf planets, etc.), comprise our *solar system*.

Warmth for the planets is provided primarily by the sun's energy. At an average distance from the sun of nearly 150 million kilometers (km) or 93 million miles (mi), Earth intercepts only a very small fraction of the sun's total energy output. However, it is this *radiant energy* (or *radiation*)[**] that drives the atmosphere into the patterns of everyday wind and weather and allows Earth to maintain an average surface temperature of about 15°C (59°F).[†] Although this temperature is mild, Earth experiences a wide range of temperatures, as readings can drop below –85°C (–121°F) during a frigid Antarctic night and climb, during the day, to above 50°C (122°F) on the oppressively hot subtropical desert.

Earth's *atmosphere* is a relatively thin, gaseous envelope comprised mostly of nitrogen and oxygen, with small amounts of other gases, such as water vapor and carbon dioxide. Nestled in the atmosphere are clouds of liquid water and ice crystals. Although our atmosphere extends upward for many hundreds of kilometers, it gets progressively thinner with altitude. Almost 99 percent of the atmosphere lies within a mere 30 km (19 mi) of Earth's surface (see ● Fig. 1.3). In fact, if Earth were to shrink to the size of a beach ball, its inhabitable atmosphere would be thinner than a piece of paper. This thin blanket of air constantly shields the surface and its inhabitants from the sun's dangerous ultraviolet radiant energy, as well as from the onslaught of material from interplanetary space. There is no definite upper limit to the atmosphere; rather, it becomes thinner and thinner, eventually merging with empty space, which surrounds all the planets.

THE EARLY ATMOSPHERE The atmosphere that originally surrounded Earth was probably much different from the air we breathe today. Earth's first atmosphere (some 4.6 billion years ago) was most likely *hydrogen* and *helium*—the two most abundant gases found in the universe—as well as hydrogen compounds, such as methane (CH_4) and ammonia (NH_3). Most scientists believe that this early atmosphere escaped into space from Earth's hot surface.

A second, more dense atmosphere, however, gradually enveloped Earth as gases from molten rock within its hot interior escaped through volcanoes and steam vents. We assume that volcanoes spewed out the same gases then as they do today: mostly water vapor (about 80 percent), carbon dioxide (about 10 percent), and up to a few percent nitrogen. These gases (mostly water vapor and carbon dioxide) probably created Earth's second atmosphere.

As millions of years passed, the constant outpouring of gases from the hot interior—known as **outgassing**—provided a rich supply of water vapor, which formed into clouds. (It is also believed that when Earth was very young, some of its water may have originated from numerous collisions with small meteors that pounded Earth, as well as from disintegrating comets.) Rain fell upon Earth for many thousands of years, forming the rivers, lakes, and oceans of the world. During this time, large amounts of carbon dioxide (CO_2) were dissolved in the oceans.

NASA/JSC

● **FIGURE 1.3** Earth's atmosphere as viewed from space. The atmosphere is the thin bluish-white region along the edge of Earth. The photo was taken from the International Space Station on April 12, 2011, over western South America.

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[*] Pluto was once classified as a true planet. But recently it has been reclassified as a planetary object called a *dwarf planet.*

[**] Radiation is energy transferred in the form of waves that have electrical and magnetic properties. The light that we see is radiation, as is ultraviolet light. More on this important topic is given in Chapter 2.

[†] The abbreviation °C is used when measuring temperature in degrees Celsius, and °F is the abbreviation for degrees Fahrenheit. More information about temperature scales is given in Appendix A and in Chapter 2.

▼Table 1.1 Composition of the Atmosphere near the Earth's Surface

PERMANENT GASES			VARIABLE GASES			
Gas	Symbol	Percent (by Volume) Dry Air	Gas (and Particles)	Symbol	Percent (by Volume)	Parts per Million (ppm)*
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.040	400*
Argon	Ar	0.93	Methane	CH_4	0.00018	1.8
Neon	Ne	0.0018	Nitrous oxide	N_2O	0.00003	0.3
Helium	He	0.0005	Ozone	O_3	0.000004	0.04†
Hydrogen	H_2	0.00006	Particles (dust, soot, etc.)		0.000001	0.01–0.15
Xenon	Xe	0.000009	Chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs)		0.00000001	0.0001

*For CO_2, 400 parts per million means that out of every million air molecules, 400 are CO_2 molecules.
†Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.

Through chemical and biological processes, much of the CO_2 became locked up in carbonate sedimentary rocks, such as limestone. With much of the water vapor already condensed and the concentration of CO_2 dwindling, the atmosphere gradually became rich in molecular nitrogen (N_2), which is usually not chemically active.

It appears that molecular oxygen (O_2), the second most abundant gas in today's atmosphere, probably began an extremely slow increase in concentration as energetic rays from the sun split water vapor (H_2O) into hydrogen and oxygen during a process called *photodissociation.* The hydrogen, being lighter, probably rose and escaped into space, while the oxygen remained in the atmosphere.

This slow increase in oxygen may have provided enough of this gas for primitive plants to evolve, perhaps 2 to 3 billion years ago. Or the plants may have evolved in an almost oxygen-free (anaerobic) environment. At any rate, plant growth greatly enriched our atmosphere with oxygen. The reason for this enrichment is that, during the process of *photosynthesis*, plants, in the presence of sunlight, combine carbon dioxide and water to produce oxygen. Hence, after plants evolved, the atmospheric oxygen content increased more rapidly, probably reaching its present composition about several hundred million years ago.

COMPOSITION OF TODAY'S ATMOSPHERE

▼Table 1.1 shows the various gases present in a volume of air near Earth's surface. Notice that molecular **nitrogen** (N_2) occupies about 78 percent and molecular **oxygen** (O_2) about 21 percent of the total volume of dry air. If all the other gases are removed, these percentages for nitrogen and oxygen hold fairly constant up to an elevation of about 80 km (50 mi). (For a closer look at the composition of a breath of air at Earth's surface, read Focus section 1.1.)

At the surface, there is a balance between destruction (output) and production (input) of these gases. For example, nitrogen is removed from the atmosphere primarily by biological processes that involve soil bacteria. In addition, nitrogen is taken from the air by tiny ocean-dwelling plankton that convert it into nutrients that help fortify the ocean's food chain. It is returned to the atmosphere mainly through the decaying of plant and animal matter. Oxygen, on the other hand, is removed from the atmosphere when organic matter decays and when oxygen combines with other substances, producing oxides. It is also taken from the atmosphere during breathing, as the lungs take in oxygen and release carbon dioxide (CO_2). The addition of oxygen to the atmosphere occurs during photosynthesis, as plants, in the presence of sunlight, combine carbon dioxide and water to produce sugar and oxygen.

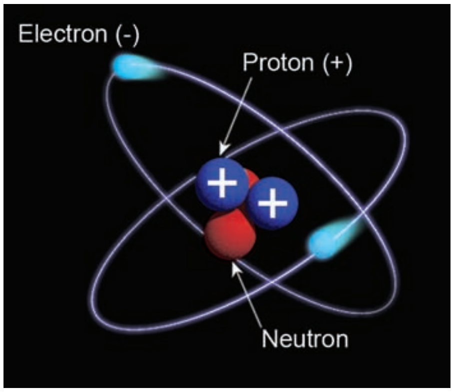
The concentration of the invisible gas **water vapor** (H_2O), however, varies greatly from place to place, and from time to time. Close to the surface in warm, steamy, tropical locations, water vapor may account for up to 4 percent of the atmospheric gases: whereas in colder arctic areas, its concentration may dwindle to a mere fraction of a percent (see Table 1.1). Water vapor molecules are, of course, invisible. They become visible only when they transform into larger liquid or solid particles, such as cloud droplets and ice crystals, which may grow in size and eventually fall to Earth as rain or snow. The changing of water vapor into liquid water is called *condensation,* whereas the process of liquid water becoming water vapor is called *evaporation.* The falling rain and snow is called *precipitation.* In the lower atmosphere, water is everywhere. It is the only substance that exists as a gas, a liquid, and a solid at those temperatures and pressures normally found near Earth's surface (see ● Fig. 1.4).

Water vapor is an extremely important gas in our atmosphere. Not only does it form into both liquid and solid cloud particles that grow in size and fall to Earth as *precipitation,* but it also releases large amounts of heat—called *latent heat*—when it changes from vapor into liquid water or ice. Latent heat is an important source of atmospheric energy, especially for storms, such as thunderstorms and hurricanes. Moreover, water vapor

FOCUS ON A SPECIAL TOPIC 1.1

A Breath of Fresh Air

If we could examine a breath of air, we would see that air (like everything else in the universe) is composed of incredibly tiny particles called *atoms*. We cannot see atoms individually with the naked eye. Yet, if we could see one, we would find electrons whirling at fantastic speeds about an extremely dense center, somewhat like hummingbirds darting and circling about a flower. At this center, or nucleus, are the protons and neutrons. Almost all of the atom's mass is concentrated here, in a trillionth of the atom's entire volume. In the nucleus, the proton carries a positive charge, whereas the neutron is electrically neutral. The circling electron carries a negative charge. As long as the total number of protons in the nucleus equals the number of orbiting electrons, the atom as a whole is electrically neutral (see ● Fig. 1).



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● **FIGURE 1** An atom has neutrons and protons at its center with electrons orbiting this center (or nucleus). Molecules are combinations of two or more atoms. The air we breathe is mainly molecular nitrogen (N_2) and molecular oxygen (O_2).

Most of the air particles are *molecules,* combinations of two or more atoms (such as nitrogen, N_2, and oxygen, O_2), and most of the molecules are electrically neutral. A few, however, are electrically charged, having lost or gained electrons. These charged atoms and molecules are called *ions.*

An average breath of fresh air contains a tremendous number of molecules. With every deep breath, trillions of molecules from the atmosphere enter your body. Some of these inhaled gases become a part of you, and others are exhaled.

The volume of an average size breath of air is about a liter.* Near sea level, there are roughly ten thousand million million million (10^{22})* air molecules in a liter. So,

$$1 \text{ breath of air} = 10^{22} \text{ molecules}$$

We can appreciate how large this number is when we compare it to the number of stars in the universe. Astronomers estimate that there are about 500 billion (10^{11}) stars in the Milky Way, which is considered to be an average sized galaxy, and that there may be more than 10^{11} galaxies in the universe. To determine the total number of stars in the universe, we multiply the average number of stars in a galaxy by the total number of galaxies and obtain

$$(5 \times 10^{11}) \times 10^{11} = 5 \times 10^{22} \text{ stars in the universe}$$

Therefore, just a few breaths of air contain about as many molecules as there are stars in the known universe.

In the entire atmosphere, there are nearly 10^{44} molecules. The number 10^{44} is 10^{22} squared; consequently

$$10^{22} \times 10^{22} = 10^{44} \text{ molecules in the atmosphere}$$

We thus conclude that there are about 10^{22} breaths of air in the entire atmosphere. In other words, there are as many molecules in a single breath as there are breaths in the atmosphere.

Each time we breathe, the molecules we exhale enter the turbulent atmosphere. If we wait a long time, those molecules will eventually become thoroughly mixed with all of the other air molecules. If none of the molecules were consumed in other processes, eventually there would be a molecule from that single breath in every breath that is out there. So, considering the many breaths people exhale in their lifetimes, it is possible that in our lungs are molecules that were once in the lungs of people who lived hundreds or even thousands of years ago. In a very real way then, we all share the same atmosphere.

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*One cubic centimeter is about the size of a sugar cube, and there are a thousand cubic centimeters in a liter.

**The notation 10^{22} means the number one followed by twenty-two zeros. For a further explanation of this system of notation see Appendix A.

is a potent *greenhouse gas* because it strongly absorbs a portion of Earth's outgoing radiant energy (somewhat like the glass of a greenhouse prevents the heat inside from escaping and mixing with the outside air). This trapping of heat energy close to Earth's surface—called the *greenhouse effect*—keeps the average air temperature near the surface much warmer than it would be otherwise.* Thus, water vapor plays a significant role in Earth's heat-energy balance.

Carbon dioxide (CO_2), a natural component of the atmosphere, occupies a small (but important) percent of a volume of air, about 0.04 percent. Carbon dioxide enters the atmosphere mainly from the decay of vegetation, but it also comes from volcanic eruptions, the exhalations of animal life, from the burning of fossil fuels (such as coal, oil, and natural gas), and from deforestation. The removal of CO_2 from the atmosphere takes place during photosynthesis, as plants consume CO_2 to produce green matter. The CO_2 is then stored in roots, branches, and leaves. Rain and snow can react with silicate minerals in rocks and remove CO_2 from the atmosphere through a process known as *chemical weathering*. The oceans act as a huge reservoir for CO_2, as phytoplankton (tiny drifting plants) in surface water fix CO_2 into organic tissues. Carbon dioxide that dissolves directly into surface water mixes downward and circulates through greater depths. Estimates are that the oceans hold more than 50 times the total atmospheric CO_2 content. ● Figure 1.5 illustrates important ways carbon dioxide enters and leaves the atmosphere.

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*A more detailed look at the greenhouse effect is presented in Chapter 2.

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FIGURE 1.4 Earth's atmosphere is a rich mixture of many gases, with clouds of condensed water vapor and ice crystals. Here, water evaporates from the ocean's surface. Rising air currents then transform the invisible water vapor into many billions of tiny liquid droplets that appear as puffy cumulus clouds. If the rising air in the cloud should extend to greater heights, where air temperatures are quite low, some of the liquid droplets would freeze into minute ice crystals.

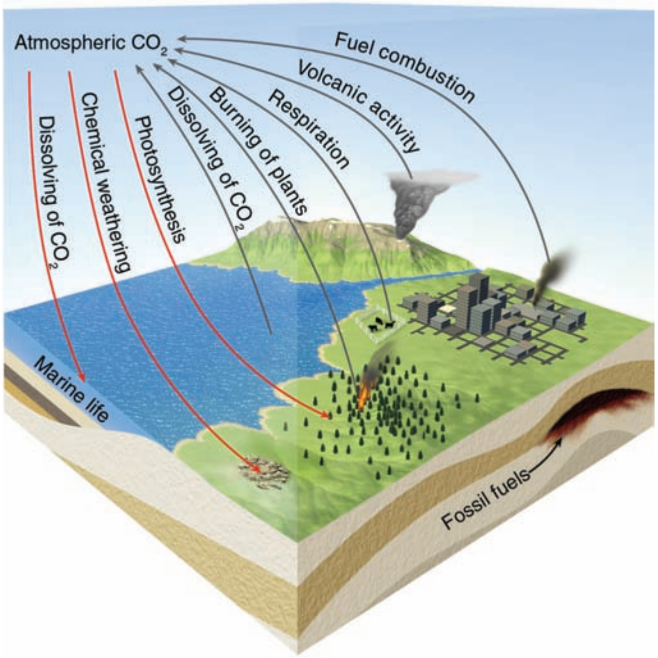

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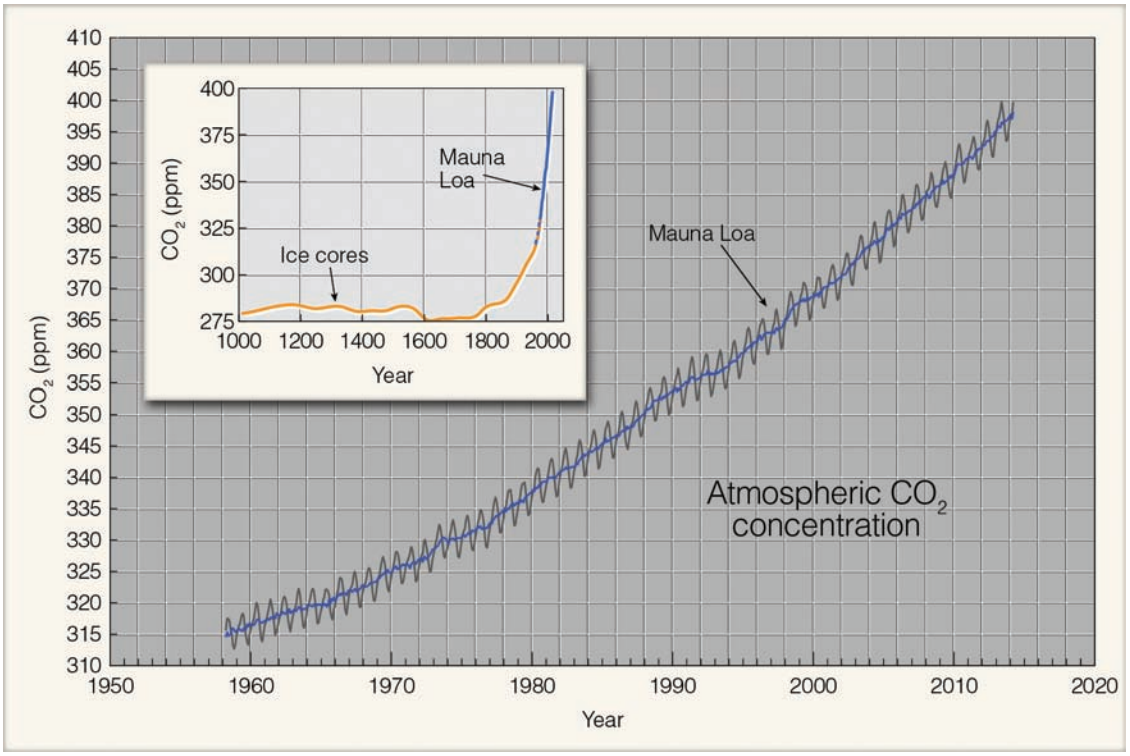
FIGURE 1.5 The main components of the atmospheric carbon dioxide cycle. The gray lines show processes that put carbon dioxide into the atmosphere, whereas the red lines show processes that remove carbon dioxide from the atmosphere.

Figure 1.6 reveals that the atmospheric concentration of CO_2 has risen by almost 30 percent since 1958, when regular measurements began at Mauna Loa Observatory in Hawaii. This increase means that CO_2 is entering the atmosphere at a greater rate than it is being removed. The increase appears to be due mainly to the burning of fossil fuels; however, deforestation also plays a role as cut timber, burned or left to rot, releases CO_2 directly into the air, perhaps accounting for about 10 to 15 percent of the observed increase in recent years. Measurements of CO_2 also come from ice cores. In Greenland and Antarctica, for example, tiny bubbles of air trapped within the ice sheets reveal that before the industrial revolution, CO_2 levels were stable at about 280 parts per

FIGURE 1.6 (a) The solid blue line shows the average yearly measurements of CO_2 in parts per million (ppm) at Mauna Loa Observatory, Hawaii, from 1958 to 2013. The jagged dark line illustrates how higher readings occur in winter where plants die and release CO_2 to the atmosphere, and how lower readings occur in summer when more abundant vegetation absorbs CO_2 from the atmosphere. (b) The insert shows CO_2 values in ppm during the past 1000 years from ice cores in Antarctica (orange line) and from Mauna Loa Observatory (blue line). (Mauna Loa data courtesy of NOAA; Ice Core data courtesy of Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory)



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million (ppm). (See the insert in Fig. 1.6.) Since the early 1800s, however, CO_2 levels have increased more than 40 percent. With CO_2 levels presently increasing by more than 0.5 percent annually (2.0 ppm/year), scientists now estimate that the concentration of CO_2 will likely rise from its current value of about 400 ppm to a value exceeding 550 ppm by the end of this century, assuming that fossil fuel emissions continue at or above current levels.

Carbon dioxide is another important greenhouse gas because, like water vapor, it traps a portion of Earth's outgoing energy. Consequently, with everything else being equal, as the atmospheric concentration of CO_2 increases, so should the average global surface air temperature. In fact, over the last 100 years or so, Earth's average surface temperature has warmed by more than 0.8°C (1.4°F). Mathematical climate models that predict future atmospheric conditions estimate that if concentrations of CO_2 (and other greenhouse gases) continue to increase at or beyond their present rates, Earth's surface could warm by an additional 3°C (5.4°F) or more by the end of this century. As we will see in Chapter 18, the negative consequences of this type of *climate change* (such as rising sea levels and the rapid melting of polar ice) will be felt worldwide.

Carbon dioxide and water vapor are not the only greenhouse gases. Others include *methane* (CH_4), *nitrous oxide* (N_2O) and *chlorofluorocarbons* (CFCs). On average, methane concentrations have risen about one-half of one percent per year since the 1990s, but the pace has been uneven for reasons now being studied. Most methane appears to derive from the breakdown of plant material by certain bacteria in rice paddies, wet oxygen-poor soil, the biological activity of termites, and biochemical reactions in the stomachs of cows, although some methane is also leaked into the atmosphere by natural gas operations. Levels of nitrous oxide—commonly known as laughing gas—have also been rising annually at the rate of about one-quarter of a percent. As well as being an industrial byproduct, nitrous oxide forms in the soil through a chemical process involving bacteria and certain microbes. Ultraviolet light from the sun destroys nitrous oxide.

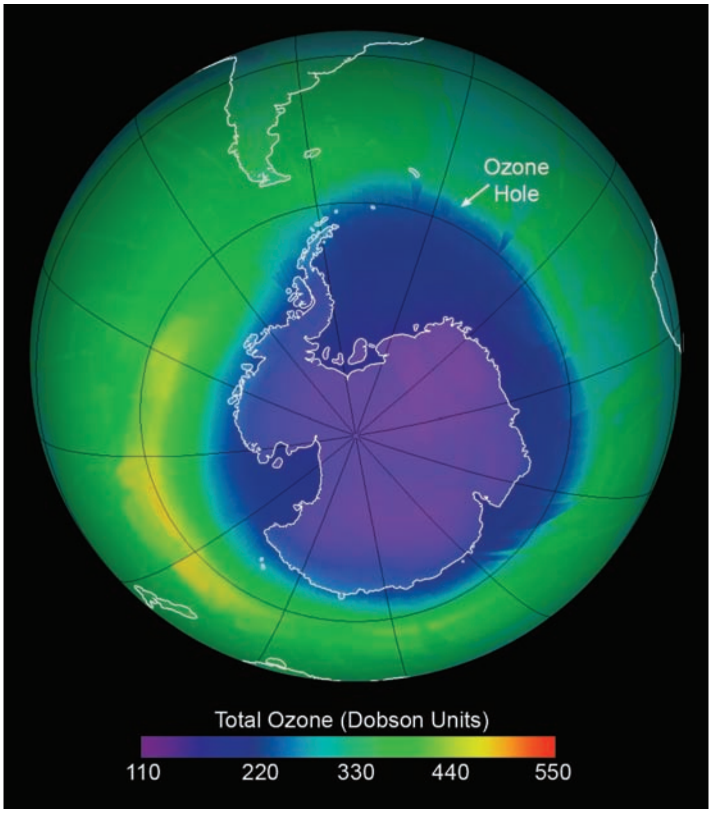
Chlorofluorocarbons (CFCs) represent a group of greenhouse gases that, up until the mid-1990s, had been increasing in concentration. At one time, they were the most widely used propellants in spray cans. More recently, they have been used as refrigerants, as propellants for the blowing of plastic-foam insulation, and as solvents for cleaning electronic microcircuits. Although their average concentration in a volume of air is quite small (see Table 1.1, p. 6), CFCs have an important effect on our atmosphere as they not only have the potential for raising global temperatures, they also play a part in destroying the gas ozone in the stratosphere, a region in the atmosphere located between about 11 km and 50 km above Earth's surface. CFCs are gradually being phased out through a global agreement called the Montreal Protocol. Their main replacements, hydrofluorocarbons (HFCs), do not damage stratospheric ozone, but they are still powerful greenhouse gases.

On Earth's surface, **ozone** (O_3) is the primary ingredient of *photochemical smog,** pollution which irritates the eyes and throat and damages vegetation. But the majority of atmospheric ozone (about 97 percent) is found in the upper atmosphere—in the stratosphere—where it is formed naturally, as oxygen atoms combine with oxygen molecules. Here, the concentration of ozone averages less than 0.002 percent by volume. This small quantity is important, however, because it shields plants, animals, and humans from the sun's harmful ultraviolet rays. It is ironic that ozone, which damages plant life in a polluted environment, provides a natural protective shield in the upper atmosphere so that plants on the surface may survive.

WEATHER WATCH

When it rains, it rains pennies from heaven—sometimes. On July 17, 1940, a tornado reportedly picked up a treasure of over 1000 sixteenth-century silver coins, carried them into a thunderstorm, then dropped them on the village of Merchery in the Gorki region of Russia.

When CFCs enter the stratosphere, ultraviolet rays break them apart, and the CFCs release ozone-destroying chlorine. Because of this effect, ozone concentration in the stratosphere has decreased over parts of the Northern and Southern Hemispheres. ● Figure 1.7 illustrates the extent of ozone depletion above Antarctica during September 2010. Stratospheric ozone concentrations plummet each year during September and October above Antarctica, to the point where so little ozone is observed



● **FIGURE 1.7** The darkest color represents the area of lowest ozone concentration, or ozone hole, over the Southern Hemisphere on September 25, 2010. Notice that the hole is larger than the continent of Antarctica. A Dobson unit (DU) is the physical thickness of the ozone layer if it were brought to Earth's surface, where 500 DU equals 5 millimeters.

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*Originally the word *smog* meant the combining of smoke and fog. Today, however, the word usually refers to the type of smog that forms in large cities, such as Los Angeles, California. Because this type of smog forms when chemical reactions take place in the presence of sunlight, it is termed *photochemical smog*.