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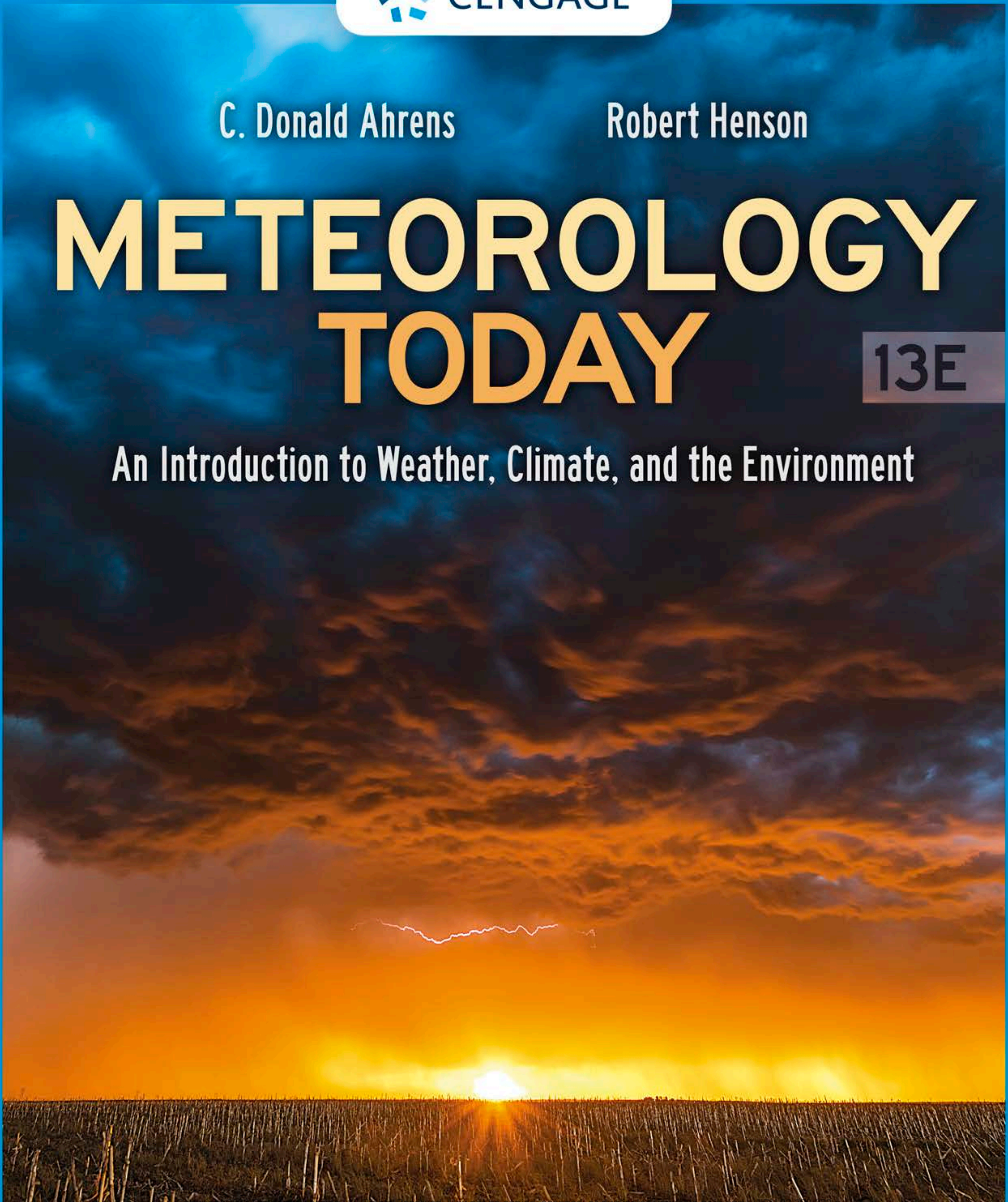
C. Donald Ahrens
Robert Henson

METEOROLOGY TODAY

13E

An Introduction to Weather, Climate, and the Environment



13TH EDITION

METEOROLOGY TODAY

AN INTRODUCTION TO WEATHER, CLIMATE, AND THE ENVIRONMENT

C. Donald Ahrens
Emeritus, Modesto Junior College

Robert Henson

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Contents in Brief

Contents


© C. Donald Ahrens


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CHAPTER 6

Stability and Cloud Development 145

CHAPTER 7

Precipitation 169


© Robert Henson


© Robert Henson

CHAPTER 10

Wind: Global Systems 265

CHAPTER 11

Air Masses and Fronts 297

CHAPTER 12

Middle-Latitude Cyclones 325

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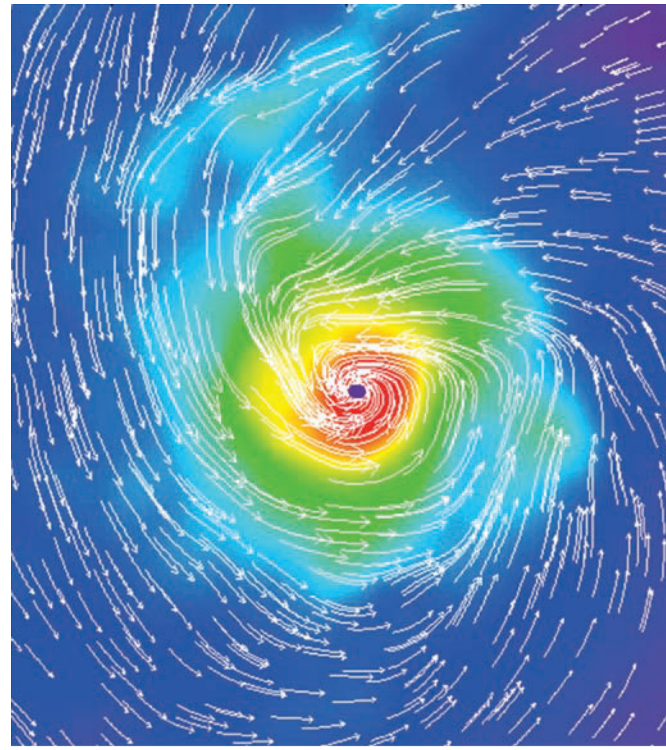
CHAPTER 13

Weather Forecasting 351



NASA

CHAPTER 14

Thunderstorms 389

CHAPTER 15

CHAPTER 16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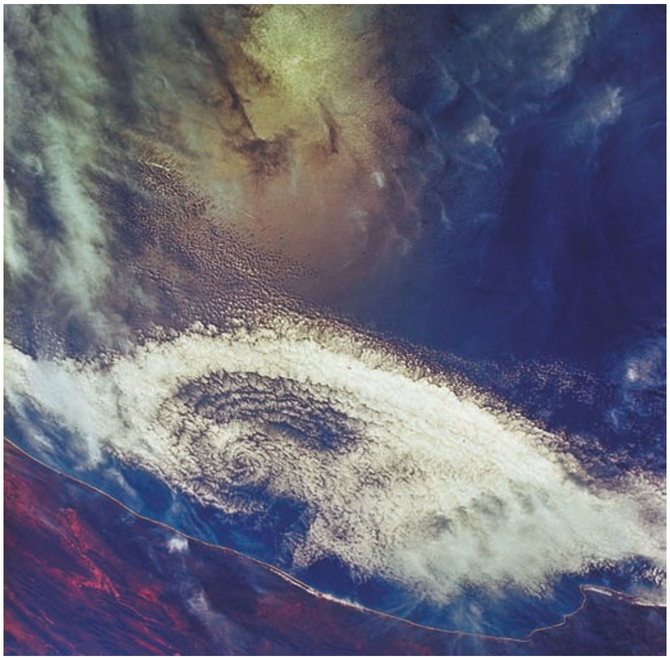
CHAPTER 17

CHAPTER 18



NASA

CHAPTER 19

Air Pollution 551

CHAPTER 20

Light, Color, and Atmospheric Optics 581

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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 and climate change seem to receive an ever-increasing amount of coverage. From the destruction wrought by extreme storms to the quiet, but no less devastating, impacts of severe drought, weather has an enormous impact on our lives. The longer-term effects of human-produced greenhouse gases on climate also demand our attention, whether it be rising sea levels, 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. 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 thirteenth edition includes up-to-date information on many important topics, including climate change, ozone depletion, air quality, 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. A Cloud Chart included with the print edition can be separated from the book and used as a learning tool in any place one chooses to observe the sky. Hundreds of 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 separate 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 they can be covered in any desired order, tailoring the book to their particular needs. For example, the chapter on atmospheric optics, Chapter 20, is self-contained and can be covered before or after any chapter.

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 "Weather and the Flu: It's Not the Cold, It's the Humidity," (Chapter 4), "North America's Own Monsoon" (Chapter 9), "When Winter Went AWOL: The Extreme Positive AO Winter of 2019–2020" (Chapter 10), "Fire Tornadoes: The Unusual Spinoffs of Wildfires" (Chapter 15), and "Is Carbon Dioxide a Pollutant?" (Chapter 19). 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 list of learning objectives 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.

Eight 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.

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

Instructor Companion Website Everything you need for your course in one place! This collection of book-specific lecture and class tools is available online via www.cengage.com/login. Access and download PowerPoint presentations, images, instructor's manual, and more.

Cognero Test Bank Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to:

- Author, edit, and manage test bank content from multiple Cengage Learning solutions
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Meteorology Today MindTap MindTap for Ahrens: Meteorology Today, 13th Edition, is the digital learning solution that powers students from memorization to mastery. It gives you complete control of your course—to provide engaging content and to challenge every individual—and empowers students to build their confidence and to improve their progress and performance.

MindTap for Meteorology is designed to ensure class preparedness through concept check activities; increase conceptual understanding through high-quality visualizations, including animations and videos; and improve critical-thinking skills through homework activities that solidify concepts at an appropriately rigorous level.

TECHNOLOGY FOR THE STUDENT

MindTap for Ahrens, Meteorology Today, 13th Edition, helps students learn on their terms. MindTap allows students instant access in their pocket. Students can take advantage of the Cengage Mobile App to learn on their terms. They can read or listen to textbooks and study with the aid of instructor notifications, flashcards, and practice quizzes.

Students can track their own scores and stay motivated toward their goals. Whether they have more work to do or are ahead of the curve, they'll know where they need to focus their efforts.

Students can also create custom flashcards, highlight key sections in their textbook they want to remember, complete homework assigned by their instructor, and watch videos and animations to help strengthen their understanding of lecture and reading material.

Changes in the Thirteenth Edition

The authors have carried out extensive updates and revisions to this thirteenth edition of *Meteorology Today*, reflecting the ever-changing nature of the field and the atmosphere itself. New or revised color illustrations and new photos have been added to help visualize the excitement of the atmosphere. The topic of climate change, of great interest to students and society at large, is addressed throughout the textbook.

- 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 lays the foundation for the rest of the book. The section on Earth's early atmosphere has been substantially revised to reflect new findings. Among recent events now referenced in this chapter are destructive hurricane landfalls of 2017, 2018, and 2019 and the catastrophic California wildfires of 2017 and 2018.
- Chapter 2, "Energy: Warming and Cooling Earth and the Atmosphere," contains up-to-date statistics and background on greenhouse gases and climate change, topics covered in more detail later in the book. The section on UV radiation and skin protection has been updated to reflect changes in sunscreen formulation and recent trends in skin cancer.
- Chapter 3, "Seasonal and Daily Temperatures," includes several updates to a wide range of tables, maps, and narrative describing various extremes in temperature. A new figure shows state-by-state high and low temperature records.
- Chapter 4, "Atmospheric Humidity," continues to cover essential concepts related to this important aspect of the atmosphere. The section on humidity measurement has been extensively revised to reflect evolving technology and operational practice in this area. A new Focus box spotlights the connection between atmospheric humidity, seasonality, and influenza transmission, a topic of particular interest in the wake of the novel coronavirus pandemic.

- Chapter 5, "Condensation: Dew, Fog, and Clouds," includes updates to the discussion of tule fog and noctilucent clouds, based on multidecadal trends in both of these cloud types. New products from GOES-17 are employed in the section discussing visible and infrared satellite imagery.
- Chapter 6, "Stability and Cloud Development," continues to discuss atmospheric stability and instability and the resulting effects on cloud formation in a carefully sequenced manner. Numerous illustrations and several Focus sections help to make these complex concepts understandable.
- "Precipitation" (Chapter 7) includes updates to the sections discussing the Wegener-Bergeron-Findeisen process, cloud seeding, snow squalls, blizzards, aircraft icing, and the economic impact of hailstorms. A new Weather Watch box covers the phenomenon of graupel falling into relatively mild surface air.
- Chapter 8, "Air Pressure and Winds," includes a recently enhanced description and revised illustrations of the interplay between the pressure gradient and Coriolis forces in cyclonic and anticylonic flow. A new Weather Watch box spotlights the record-high atmospheric pressure recorded in London in 2020.
- Chapter 9, "Wind: Small-Scale and Local Systems," discusses the catastrophic California wildfires of 2017 and 2018 in the context of localized winds. The discussion of the Asian monsoon now includes more specifics on monsoon-related features over East and South Asia. A new Focus box discusses the North American Monsoon.
- Chapter 10, "Wind: Global Systems," includes enhanced information on La Niña and a new section on the Indian Ocean Dipole. A new Focus box covers the extreme positive Arctic Oscillation of 2019–2020 and its influence on the Northern Hemisphere winter.
- In Chapter 11, "Air Masses and Fronts," the concept of cold fronts aloft and their relationship to warm-sector thunderstorms has been added.
- Chapter 12, "Middle-Latitude Cyclones," continues to provide a thorough and accessible introduction to this important topic. Narrative and artwork related to the concept of conveyor belts has been updated.
- Chapter 13, "Weather Forecasting," retains the major restructuring launched in the previous edition. Among the topics newly referenced in this edition are the NOAA Unified Forecast System and the increased importance of aircraft data in numerical modeling.
- Chapter 14, "Thunderstorms," provides a colorful and comprehensive introduction to the wide variety of thunderstorm-related processes and phenomena. The topics of pyrocumulonimbus and anvil-crawler lightning have been added, and the Focus section on transient electrical phenomena, including sprites, has undergone a major revision and expansion.
- Chapter 15, "Tornadoes," includes a new Focus section on whirlwinds and tornadic circulations related to wildfires. A number of tornado-related statistics have been updated, and forthcoming changes to the Enhanced Fujita Scale are noted.
- Chapter 16, "Hurricanes," has been substantially revised, including new sections on hurricanes Michael (2018) and Dorian (2019). The chapter also includes enhanced discussion of hurricane observing techniques, as well as updated findings on hurricanes and climate change. The definitions of tropical depressions, tropical storms, and tropical cyclones—including post-tropical and subtropical cyclones—are now introduced closer to the front of the chapter.
- Chapter 17, "Global Climate," continues to serve as a convenient stand-alone unit on global climatology and classification schemes.
- Chapter 18, "Earth's Changing Climate," has undergone a thorough update to reflect recent developments and findings, including major global heat and precipitation events, the 2018 report "Global Warming of 1.5°C" from the Intergovernmental Panel on Climate Change, and the wide variety of proposed approaches to mitigating climate change.
- Chapter 19, "Air Pollution," reflects a number of updates, including the vast number of deaths associated with both indoor and outdoor air pollution and the importance of the smallest airborne particulates as a health hazard. A new Focus box explores the question of how and when carbon dioxide can be considered a pollutant.
- 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 thirteenth edition of *Meteorology Today*. A special thanks goes to Charles Preppernau for his contributions in rendering beautiful artwork and to Mabel Labiak for professional and conscientious proofreading. We are indebted to the team at SPi Global, including Pradhiba Kannaiyan and Linda Duarte, who took the photos, art, and manuscript and turned them into a beautiful end product in both print and digital forms. Thanks also go to Anjali Kambli and Haneef Abrar at Lumina Datamatics for outstanding assistance with photo research. Special thanks go to all the people at Cengage who worked on this edition, especially Vicky True, Sean Campbell, and Sarah Huber. Special thanks for comments, suggestions, images, and background information also go to Pete Akers (National Center for Scientific Research, France), Stuart Beaton and Julie Haggerty (National Center for Atmospheric Research), Christopher Bretherton (Vulcan/University of Washington), James LaDue (NOAA/NWS Warning Decision Training Division), Patrick Marsh (NOAA/NWS Storm Prediction Center), Shane Mayor (California State University, Chico), and Maureen O'Leary (National Weather Service).

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 provided 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

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

Visual Storyteller/Shutterstock.com

CHAPTER 1

Earth and Its Atmosphere

LEARNING OBJECTIVES

At the end of this section, you should be able to:

LO1 List three ways the scientific method can be applied to studying the atmosphere and weather.

LO2 Outline the sequence of changes in nitrogen, oxygen, and water vapor over Earth's history.

LO3 Explain the role of gases (including water vapor, carbon dioxide, oxygen, and other greenhouse gases) and pollutants in Earth's atmosphere.

LO4 Describe how air density and air pressure are determined and how they vary as you move upward through Earth's atmosphere.

LO5 Describe the layers of the atmosphere, including their altitudes, temperatures, compositions, and functions.

LO6 Differentiate between weather and climate.

LO7 Interpret a weather map, applying storm types and concepts such as low pressure, high pressure, and front.

LO8 List the positive and negative effects of climate and weather on human health, agriculture, infrastructure, and the economy.

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 8 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 these words 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. These concepts and ideas are part of the foundation for understanding the atmosphere and how it produces weather. They are 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.

1.1 The Atmosphere and the Scientific Method

LO1

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.)

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, sailor take warning; red sky at night, sailor's delight."

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.

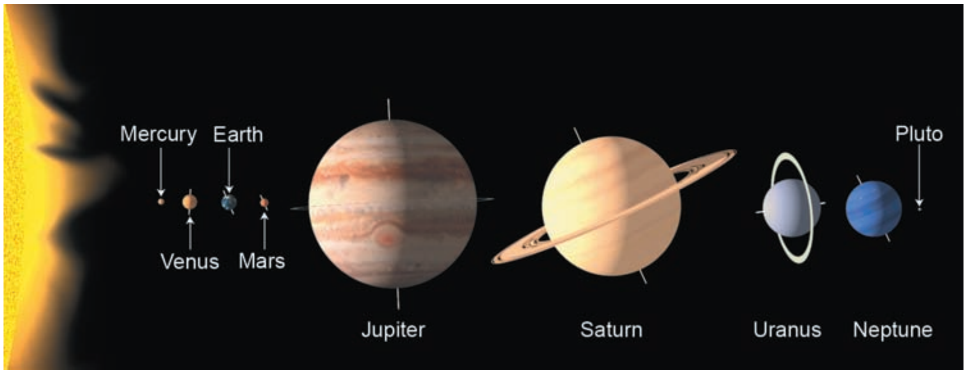
For more than 60 years, computers have given atmospheric scientists a tremendous boost. The physical laws that control atmospheric behavior can be represented in software packages known as *numerical models*. Forecasts can be made and tested many times over. The atmosphere within a model can be used to depict weather conditions from the past and project them into the future. When a model can accurately simulate past weather conditions, we can have more confidence in its portrayal of tomorrow's weather. Numerical models can also provide valuable information about the types of weather and climate we may expect decades from now.

1.2 Overview of Earth's Atmosphere

LO2 LO3

The scientific method has not only illuminated our understanding of weather and climate but also provided much information about

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



● **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.)

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

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 that comprises mostly nitrogen and oxygen, with small amounts of other gases, such as water vapor and *carbon dioxide* (CO_2). 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.

1.2a 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 originated from numerous collisions

● **FIGURE 1.3** Earth's atmosphere as viewed from space, with the moon above the horizon. The atmosphere is the thin bluish-white region along the edge of Earth. The photo was taken from the International Space Station on April 11, 2019, over the Pacific Ocean south of Hawaii.

*Pluto, discovered in 1930, was long classified as a true planet. In 2006, it was reclassified as a planetary object called a *dwarf planet*. The basis for the reclassification was that, unlike the other planets, there is much more mass distributed across smaller objects in Pluto's orbit than in Pluto itself.

**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.

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. 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 dominated by 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.

The earliest life forms on Earth were *anaerobic* bacteria, meaning they did not need oxygen to live. Anaerobic bacteria were joined in the ocean about 2.5 billion years ago by a different type—*cyanobacteria* (blue-green algae). These cyanobacteria were among the first life forms on Earth to produce oxygen. During the process of *photosynthesis*, cyanobacteria combine carbon dioxide and water in the presence of sunlight to produce sugar and oxygen.

As the cyanobacteria proliferated, they filled our oceans and eventually our atmosphere with oxygen. In fact, so much oxygen was produced that many types of anaerobic bacteria were killed off, and reactions in the atmosphere ended up producing a much colder, largely ice-covered planet. This period, from about 2.4 billion years ago to about 2 billion years ago, is known as the *Great Oxidation Event.* Oxygen levels then plummeted and stayed much lower than today's levels for more than a billion years. Eventually, other photosynthesizing life forms evolved in the oceans, and plants appeared on land. As this occurred, the atmospheric oxygen content again increased, reaching its present composition a few hundred million years ago.

1.2b 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. Nitrogen is also 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.

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

▼ 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	0.041	410*
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, 410 parts per million means that out of every million air molecules, 410 are CO_2 molecules.

**Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.

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 present 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).

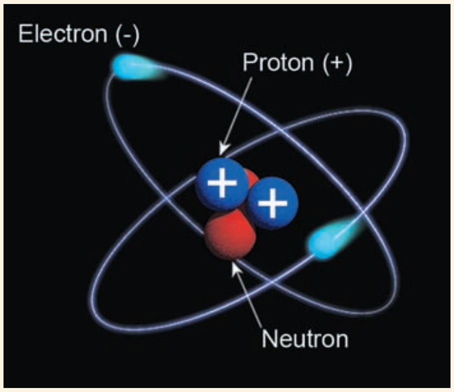
Water vapor is an extremely important gas in our atmosphere. Not only does it form into both liquid and solid cloud particles that grow in size and fall to Earth as *precipitation*, but it also releases large amounts of heat—called *latent heat*—when it changes from vapor into liquid water or ice. Latent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

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

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).



● **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

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

*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.

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,

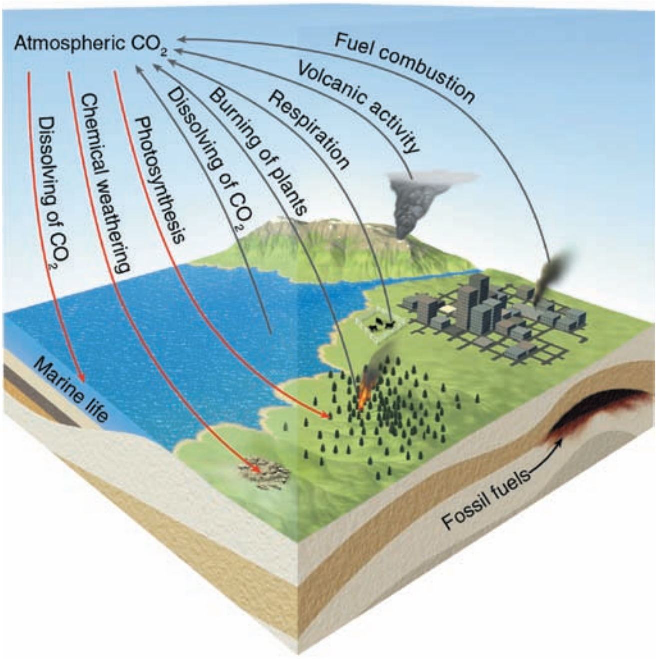
$$10^{22} \times 10^{22} = 10^{44} \text{ molecules in the atmosphere}$$

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 probable that in our lungs are molecules that were once in the lungs of people who lived hundreds or even thousands of years ago—even some of the most famous people on Earth. In a very real way then, we all share the same atmosphere.

UCAR

● **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.

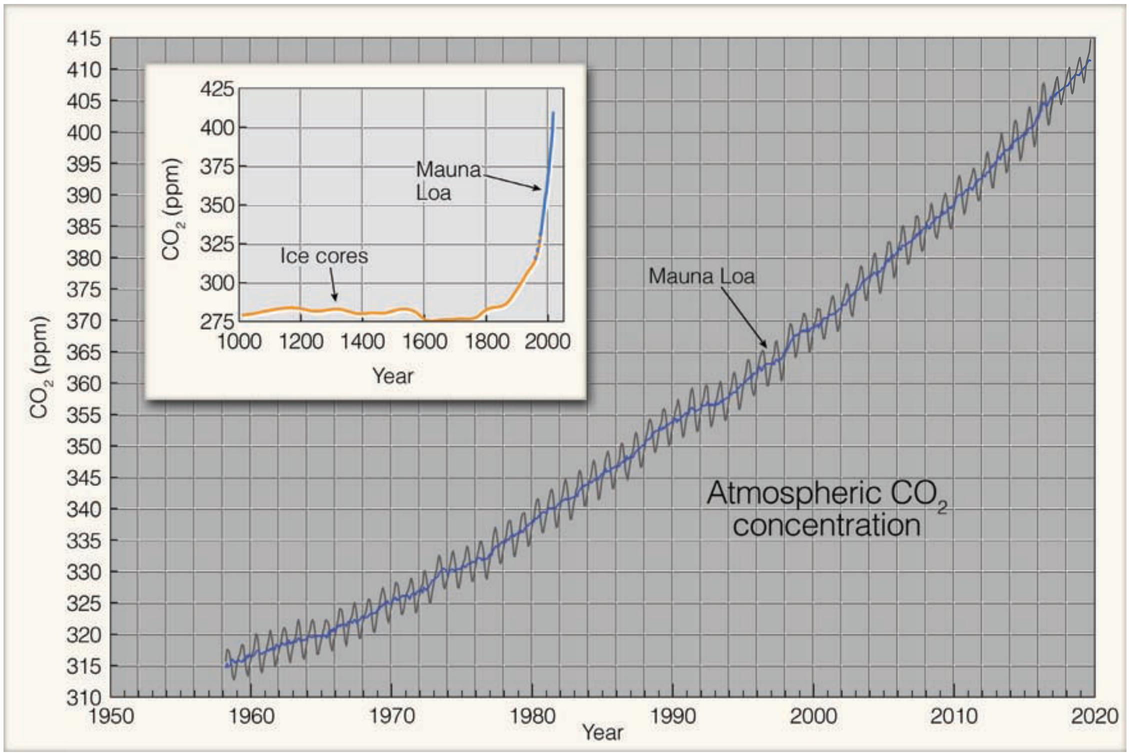


● **FIGURE 1.5** The main components of the atmospheric carbon dioxide cycle. The gray lines show processes that put carbon dioxide into the atmosphere, whereas the red lines show processes that remove carbon dioxide from the atmosphere.

Carbon dioxide (CO_2), a natural component of the atmosphere, occupies a small (but important) percent of a volume of air, just over 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.

● Figure 1.6 reveals that the atmospheric concentration of CO_2 has risen by around 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 is caused mainly by 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. In addition, these dead trees no longer remove CO_2 from the atmosphere. Deforestation accounts for about 10 to 15 percent of the observed CO_2 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 for thousands of years at about 280 parts per million (ppm). (See the insert in Fig. 1.6.) Since the early 1800s, however, CO_2 concentrations have increased more than 45 percent. Evidence from ice cores and other data indicate that there is now more CO_2 in the atmosphere than there has been in at least 3 million years. With CO_2 levels now increasing by more than 0.5 percent annually (or more than 2.0 ppm/year), the concentration of CO_2 will likely increase from its current value of more than 410 ppm to a value near 500 ppm by the middle of this century, unless major cuts to fossil fuel emissions take place in the next several decades.

Like water vapor, carbon dioxide is an important greenhouse gas that 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. Over the last 120 years or so, Earth's average surface temperature has warmed by more than 1.0°C (1.8°F). Mathematical climate models, which predict future atmospheric conditions based on our knowledge of physics and chemistry, 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 consequences of this type of *climate change*, such as intensified rainfall, rising sea levels, and the rapid melting of polar ice, are already being felt worldwide. These trends



● **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 2019. 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 inset 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)

Mauna Loa data courtesy of NOAA; Ice Core data courtesy of Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory

are expected to continue, and many other changes could occur, as long as greenhouse gases from human activity continue to accumulate in the atmosphere.

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 rose about 0.5 percent per year during the 2010s after rising at a slower rate in the previous 15 years. 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. Some methane is also leaked into the atmosphere by natural-gas operations, a topic of increased research in recent years. Concentrations of nitrous oxide—commonly known as laughing gas—have also been rising, at a rate of about 0.3 percent per year. As well as being an industrial by-product, 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 were 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. They not only act as greenhouse gases to trap heat but 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 have been almost completely 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. As a result, the Kigali Amendment to the Montreal Protocol, which came into effect in 2019, will guide the replacement of most HFCs over a 30-year period with alternatives that are much less powerful greenhouse gases.

WEATHER WATCH

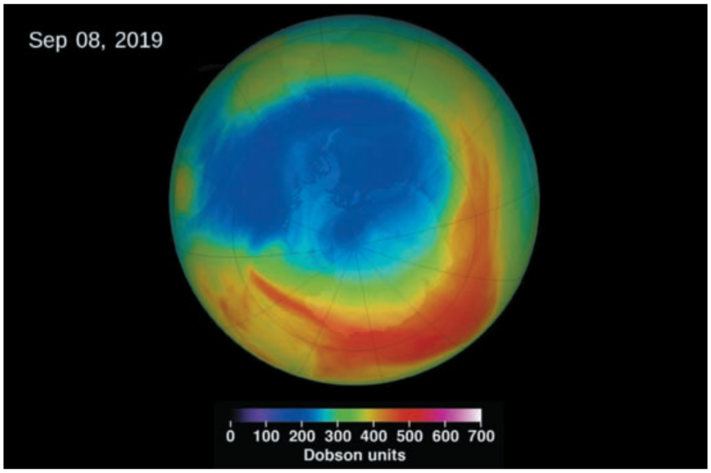
When it rains, it rains pennies from heaven—sometimes. On July 17, 1940, a tornado reportedly picked up a treasure of over 1000 sixteenth-century silver coins, carried them into a thunderstorm, then dropped them on the village of Merchery in the Gorki region of Russia.

On Earth's surface, **ozone** (O_3) is the primary ingredient of *photochemical smog*,* which irritates the eyes and throat and damages vegetation. But the majority of atmospheric ozone (about 97 percent) is found 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.

*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*.

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 decreased over parts of the Northern and Southern Hemispheres in the late twentieth century, especially over the southern polar region. ● Figure 1.7 illustrates the extent of ozone depletion above Antarctica during September 2019. Stratospheric ozone concentrations plummet each year during September and October above Antarctica, to the point where so little ozone is observed that a seasonal ozone hole forms, as shown in Fig. 1.7. (We will examine stratospheric ozone and the Antarctic **ozone hole** in more detail in Chapter 19.)

Impurities from both natural and human sources are also present in the atmosphere: Wind picks up dust and soil from Earth's surface and carries it aloft; small saltwater drops from ocean waves are swept into the air (upon evaporating, these drops leave microscopic salt particles suspended in the atmosphere); smoke from forest fires is often carried high above Earth; and volcanoes spew many tons of fine ash particles and gases into the air (see ● Fig. 1.8). Collectively, these tiny solid or liquid particles of various composition, suspended in the air, are called **aerosols**.



Goddard/Katy Mersmann/NASA

● **FIGURE 1.7** The darkest color represents the area of lowest ozone concentration, or ozone hole, over the Southern Hemisphere on September 8, 2019. 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. The Antarctic ozone hole in 2019 was the smallest for any year in records going back to 1982.

Some natural impurities found in the atmosphere are quite beneficial. Small, floating particles, for instance, act as surfaces on which water vapor condenses to form clouds. However, most human-made impurities (and some natural ones) are a nuisance, as well as a health hazard. These we call **pollutants**. For example, many older automobile engines emit copious amounts of *nitrogen dioxide* (NO_2), *carbon monoxide* (CO), and *hydrocarbons*. In sunlight, nitrogen dioxide reacts with hydrocarbons and other gases to produce photochemical smog. Carbon monoxide is a major pollutant of city air. Colorless and odorless, this poisonous gas forms during the incomplete combustion of carbon-containing fuel. Hence, more than half of carbon monoxide in urban areas comes from road vehicles, although improved emissions controls have reduced this amount in recent decades.

The burning of sulfur-containing fuels (such as coal and oil) releases sulfur gases into the air. When the atmosphere is sufficiently moist, these gases may transform into tiny dilute droplets of sulfuric acid. Similarly, nitrogen oxide can be transformed into droplets of nitric acid. Rain containing acid corrodes metals and painted surfaces, and turns freshwater lakes acidic. *Acid rain* has been a major environmental problem, especially downwind from major industrial areas. Much improvement has occurred since the 1970s in places where strict emissions controls have been put in place, including the United States and Europe. However, acid rain is still a serious concern in parts of Asia. (More on the acid rain problem is given in Chapter 19.)

● **FIGURE 1.8** Erupting volcanoes can send tons of particles into the atmosphere, along with vast amounts of water vapor, carbon dioxide, and sulfur dioxide.

David Weintraub/Science Source

Even the tiniest pollutants are a major concern. *Particulate matter* refers to solid particles and liquid droplets that are small enough to remain suspended in the air. These particles can obscure visibility and cause respiratory and cardiovascular problems. (More information on these and other pollutants is given in Chapter 19.)

BRIEF REVIEW

Before going on to the next sections, here is a review of some of the important concepts presented so far:

- Earth's atmosphere is a mixture of many gases. In a volume of dry air near the surface, nitrogen (N_2) occupies about 78 percent and oxygen (O_2) about 21 percent.
- The majority of water on our planet is believed to have come from its hot interior through outgassing, although some of Earth's water may have come from collisions with meteors and comets.
- Water vapor, which normally occupies less than 4 percent in a volume of air near the surface, can condense into liquid cloud droplets or transform into delicate ice crystals. Water is the only substance in our atmosphere that is found naturally as a gas (water vapor), as a liquid (water), and as a solid (ice).
- Both water vapor and carbon dioxide (CO_2) are important greenhouse gases. Increases in greenhouse gases from human activity are leading to global warming and other atmospheric effects.
- Ozone (O_3) in the stratosphere protects life from harmful ultraviolet (UV) radiation. At the surface, ozone is the main ingredient of photochemical smog.

1.3 Vertical Structure of the Atmosphere

LO4 LO5

When we examine the atmosphere in the vertical, we see that it can be divided into a series of layers. Each layer may be defined in a number of ways: by the manner in which the air temperature varies through it, by its gaseous composition, or even by its electrical properties. At any rate, before we examine these various atmospheric layers, we need to look at the vertical profile of two important atmospheric variables: air pressure and air density.

1.3a A BRIEF LOOK AT AIR PRESSURE AND AIR DENSITY

Air molecules (as well as everything else) are held near Earth by *gravity*. This strong, invisible force pulling down on the air squeezes (compresses) air molecules closer together, which causes their number in a given volume to increase. The more air above a level, the greater the squeezing effect or compression.

Gravity also has an effect on the weight of objects, including air. In fact, *weight* is the force acting on an object due to gravity. Weight is defined as the mass of an object times the acceleration of gravity; thus,

$$\text{weight} = \text{mass} \times \text{gravity}$$

An object's *mass* is the quantity of matter in the object. Consequently, the mass of air in a rigid container is the same everywhere in the universe. However, if you were to instantly travel to the moon, where the acceleration of gravity is much less than that of Earth, the mass of air in the container would be the same, but its weight would decrease.

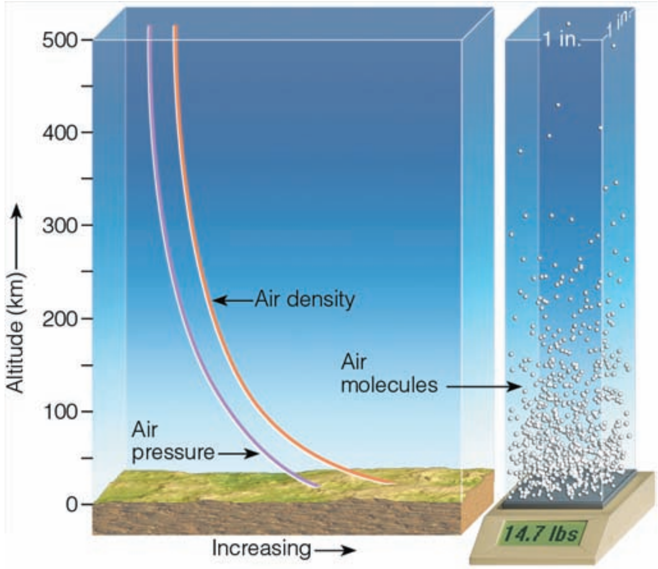
When mass is given in grams (g) or kilograms (kg), volume is given in cubic centimeters (cm^3) or cubic meters (m^3). Near sea level, air density is about 1.2 kilograms per cubic meter (nearly 1.2 ounces per cubic foot).

The **density** of air (or any substance) is determined by the masses of atoms and molecules and the amount of space between them. In other words, density tells us how much matter is in a given space (that is, volume). We can express density in a variety of ways. The molecular density of air is the number of molecules in a given volume. Most commonly, however, density is given as the mass of air in a given volume; thus,

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

Because there are appreciably more molecules within the same size volume of air near Earth's surface than at higher levels, air density is greatest at the surface and decreases as we move up into the atmosphere. Notice in ● Fig. 1.9 that, because air near the surface is compressed, air density normally decreases rapidly at first, then more slowly as we move farther away from the surface.

Air molecules are in constant motion. On a mild spring day near Earth's surface, an air molecule will collide about 10 billion times each second with other air molecules. It will also bump against objects around it—houses, trees, flowers, the ground,



● **FIGURE 1.9** Both air pressure and air density decrease with increasing altitude. The weight of all the air molecules above Earth's surface produces an average pressure near 14.7 lb/in.^{2}

and even people. Each time an air molecule bounces against a person, it gives a tiny push. This small force (push) divided by the area on which it pushes is called **pressure**; thus,

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

If we weigh a column of air 1 square inch wide, extending from the average height of the ocean surface (sea level) to the "top" of the atmosphere, it would weigh nearly 14.7 pounds (see Fig. 1.9). Thus, normal atmospheric pressure near sea level is close to 14.7 pounds per square inch (14.7 $lb/in.^2$). If more molecules are packed into the column, it becomes more dense, the air weighs more, and the surface pressure goes up. On the other hand, when fewer molecules are in the column, the air weighs less, and the surface pressure goes down. Thus, the surface air pressure can be changed by changing the mass of air above the surface.

Pounds per square inch is, of course, just one way to express air pressure. In the United States, the most common unit found on surface weather maps is the *millibar* (mb)* although the metric equivalent, the *hectopascal* (hPa), has replaced the millibar as the preferred unit of pressure on surface charts in most other countries. A more traditional unit of pressure is *inches of mercury* (in. Hg), which is commonly used in the field of aviation and in weather reports on television, smartphones, and the Internet. At sea level, the *standard value* for atmospheric pressure is

$$1013.25 \text{ mb} = 1013.25 \text{ hPa} = 29.92 \text{ in. Hg}$$

Billions of air molecules push constantly on the human body. This force is exerted equally in all directions. We are not crushed by it because billions of molecules inside the body push outward just as hard. Even though we do not actually feel the constant bombardment of air, we can detect quick changes in it. For example, if we climb rapidly in elevation, our ears may "pop." This experience happens because air collisions outside the eardrum lessen. The popping comes about as air collisions between the inside and outside of the ear equalize. The drop in the number of collisions informs us that the pressure exerted by the air molecules decreases with height above Earth. A similar type of ear-popping occurs as we drop in elevation, and the air collisions outside the eardrum increase.

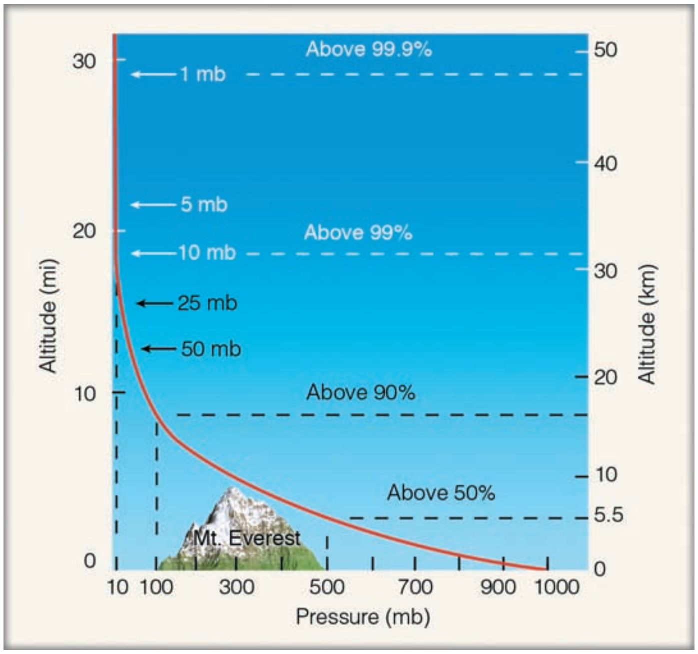
Air molecules not only take up space (freely darting, twisting, spinning, and colliding with everything around them), but—as we have seen—these same molecules have weight. In fact, air is surprisingly heavy. The weight of all the air around Earth is a staggering 5600 trillion tons, or roughly 5.08×10^{18} kg. The weight of the air molecules acts as a force upon Earth. The amount of force exerted over an area of surface is called *atmospheric pressure* or, simply, **air pressure**.* The pressure at any level in the atmosphere may be measured in terms of the total mass of air above any point. As we climb in elevation, fewer air molecules are above us; hence, *atmospheric pressure always decreases with increasing height*. Like air density, air pressure decreases rapidly at first, then more slowly at higher levels, as illustrated in Fig. 1.9.

Figure 1.10 also illustrates how rapidly air pressure decreases with height. Near sea level, atmospheric pressure is usually close to 1000 mb. Normally, just above sea level, atmospheric pressure decreases by about 10 mb for every 100 meters (m) increase in altitude—about 1 inch of mercury (Hg) for every 1000 feet (ft) of rise. At higher levels, air pressure decreases much more slowly with height. With a sea-level pressure near 1000 mb, we can see in ● Fig. 1.10 that, at an altitude of only 5.5 km (3.5 mi), the air pressure is about 500 mb, or half of the sea-level pressure. This situation means that, if you were at a mere 5.5 km (about 18,000 ft) above Earth's surface, you would be above one-half of all the molecules in the atmosphere.

At an elevation approaching the summit of Mt. Everest (about 9 km, or 29,000 ft—the highest mountain peak on Earth), the air pressure would be about 300 mb. The summit is above nearly 70 percent of all the air molecules in the atmosphere. At an altitude approaching 50 km (160,000 feet), the air pressure is about 1 mb, which means that 99.9 percent of all the air molecules are below this level. Yet the atmosphere extends upwards for many hundreds of kilometers, gradually becoming thinner and thinner until it ultimately merges with outer space. (Up to now, we have concentrated on Earth's atmosphere. For a brief look at the atmospheres of the other planets, read Focus section 1.2.)

*By definition, a *bar* is a force of 100,000 newtons (N) acting on a surface area of 1 square meter (m^2). A *newton* is the amount of force required to move an object with a mass of 1 kilogram (kg) so that it increases its speed at a rate of 1 meter per second (m/sec) each second. Because the bar is a relatively large unit, and because surface pressure changes are usually small, the unit of pressure most commonly found on surface weather maps is the *millibar*, where 1 bar = 1000 mb. The unit of pressure designated by the International System SI (Système International) of measurement is the *pascal* (Pa), where 1 pascal is the force of 1 newton acting on a surface of 1 square meter. A more common unit is the *hectopascal* (hPa), as 1 hectopascal equals 1 millibar.

*Because air pressure is measured with an instrument called a *barometer*, atmospheric pressure is often referred to as *barometric pressure*.



● **FIGURE 1.10** Atmospheric pressure decreases rapidly with height. Climbing to an altitude of only 5.5 km, where the pressure is 500 mb, would put you above one-half of the atmosphere's molecules.

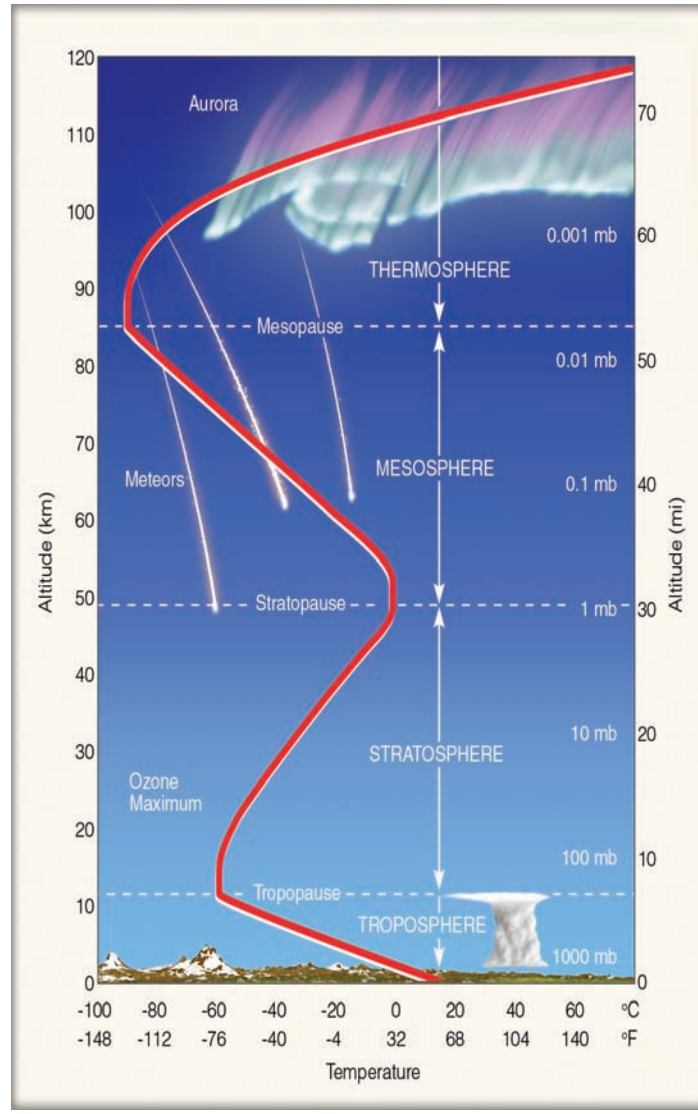
1.3b LAYERS OF THE ATMOSPHERE

Up to this point, we've looked at how both air pressure and density decrease with height above Earth—rapidly at first, then more slowly. *Air temperature*, however, has a more complicated vertical profile.*

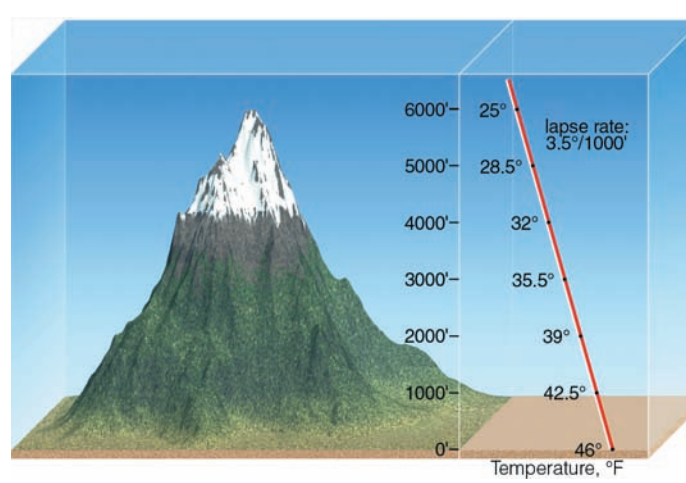
Look closely at ● Fig. 1.11 and notice that air temperature normally decreases from Earth's surface up to an altitude of about 11 km, which is nearly 36,000 ft, or 7 mi. This decrease in air temperature with increasing height is due primarily to the fact (investigated further in Chapter 2) that sunlight warms Earth's surface, and the surface, in turn, warms the air above it. The rate at which the air temperature decreases with height is called the temperature **lapse rate**. The *average* (or *standard*) *lapse rate* in this region of the lower atmosphere is about 6.5°C for every 1000 m or about 3.6°F for every 1000-ft increase in altitude. (See ● Fig. 1.12.) Keep in mind that these values are only averages. On some days, the air becomes colder more quickly as we move upward. This would increase or steepen the lapse rate. On other days, the air temperature would decrease more slowly with height, and the lapse rate would be less. Occasionally, the air temperature may actually *increase* with height, producing a condition known as a **temperature inversion**. Thus, the lapse rate fluctuates, varying from day to day, season to season, and place to place.

Fig. 1.11 shows the region of the atmosphere from the surface up to about 11 km, which contains all of the weather we are familiar with on Earth. Also, this region is kept well stirred by rising and descending air currents, and it is common for air molecules to circulate through a depth of more than 10 km in just a few days. This region of circulating air extending upward from Earth's surface to where the air stops becoming colder with height is called the **troposphere**—from the Greek *tropein*, meaning "to turn" or "to change."

Notice in Fig. 1.11 that just above 11 km the air temperature normally stops decreasing with height. Here, the lapse rate is zero. This region, where, on average, the air temperature remains constant with height, is referred to as an *isothermal* (equal temperature) *zone*.** The bottom of this zone marks the top of the troposphere and the beginning of another layer, the **stratosphere**. The boundary separating the troposphere from the stratosphere is called the **tropopause**. The height of the tropopause varies. It is normally found at higher elevations over equatorial regions, and it decreases in elevation as we travel poleward. Generally, the tropopause is higher in summer and lower in winter at all latitudes. In some regions, the tropopause "breaks" and is difficult to locate and, here, scientists have observed tropospheric air mixing with stratospheric air and vice versa. These breaks mark the position of *jet streams*—high winds that flow through the atmosphere along narrow corridors, like a swift-flowing river. Jet streams sometimes meander and at other times take a more direct path, often with wind speeds exceeding 100 knots. (For reference, a *knot* is a nautical mile per hour, where one knot equals 1.15 miles per hour [mi/hr] or 1.85 kilometers per hour [km/hr].)



● **FIGURE 1.11** Layers of the atmosphere as related to the average profile of air temperature above Earth's surface. The heavy line illustrates how the average temperature varies in each layer.



● **FIGURE 1.12** Near Earth's surface the air temperature lapse rate is often close to 3.5°F per 1000 ft. If this temperature lapse rate is present and the air temperature at the surface (0 ft) is 46°F, the air temperature about 4000 ft above the surface would be at freezing, and snow and ice might be on the ground.

Air temperature is the degree of hotness or coldness of the air and, as we will see in Chapter 2, it is also a measure of the average speed of the air molecules.

**In many instances, the isothermal layer is not present, and the air temperature begins to increase with increasing height.

FOCUS ON A SPECIAL TOPIC 1.2

The Atmospheres of Other Planets

Earth is unique in our solar system. Not only does it lie at just the right distance from the sun so that life may flourish, it also provides its inhabitants with an atmosphere rich in both molecular nitrogen and oxygen—two gases that are not abundant in the atmospheres of either Venus or Mars, our closest planetary neighbors.

The Venusian atmosphere is mainly carbon dioxide (96.5% percent) with minor amounts of water vapor and nitrogen. An opaque acid-cloud deck encircles the planet, hiding its surface. The atmosphere is quite turbulent, as instruments reveal twisting eddies and fierce winds near the top of the cloud deck in excess of 320 km/hr (200 mi/hr). This thick dense atmosphere produces a surface air pressure of about 93,000 mb, which is more than 90 times greater than that on Earth. To experience such a pressure on Earth, one would have to descend in the ocean to a depth of about 900 m (2950 ft). Moreover, this thick atmosphere of CO_2 produces a strong greenhouse effect, with a scorching-hot surface temperature of around 460°C (860°F).

The atmosphere of Mars, like that of Venus, is mostly carbon dioxide, with only small amounts of other gases, dust, and water vapor. Unlike Venus, the Martian atmosphere is very thin, and heat escapes from the surface rapidly. Thus, surface temperatures on Mars are much lower, averaging around −60°C (−76°F). NASA missions have found that liquid water sometimes flows on parts of the Martian surface, but because of the thin, cold atmosphere, there is only occasional cloud cover, and the landscape is largely barren and desertlike (see ● Fig. 2). In addition, the thin atmosphere of Mars produces an average surface air pressure of only about 6 to 7 mb, which is less than one-hundredth of that experienced at the surface of Earth. Such a pressure on Earth would be observed above the surface at an altitude near 35 km (22 mi).

Occasionally, huge dust storms develop near the Martian surface. Such storms may be accompanied by winds of several hundreds of kilometers per hour. These winds carry fine dust around the entire planet. The dust gradually settles out, coating the landscape with a thin reddish veneer.

The atmosphere of the largest planet, Jupiter, is much different from that of Venus and Mars. Jupiter's atmosphere is roughly 90 percent

NASA/JPL/Cornell

● **FIGURE 2** The Martian sky and landscape, photographed by the *Spirit* robotic rover during April 2005.

NASA

● **FIGURE 3** An image of Jupiter and the vivid cloud bands and swirls in its atmosphere, collected by the Hubble Space Telescope in April 2014.

hydrogen (H_2) and close to 10 percent helium (He), with minor amounts of methane (CH_4), ammonia (NH_3), and other compounds. A prominent feature on Jupiter is the Great Red Spot—a huge atmospheric storm about three times larger than Earth and perhaps at least 350 years old—that spins counterclockwise in Jupiter's southern hemisphere (see ● Fig. 3). Large white ovals near the Great Red Spot are similar but smaller storm systems. Not only does Jupiter have lightning, but each flash is typically several times more intense than the ones we see on Earth. Unlike Earth's weather machine, which is driven by the sun, Jupiter's massive swirling clouds appear to be driven by a collapsing core of hot hydrogen. Energy from this lower region rises toward the surface; then it (along with Jupiter's rapid rotation) stirs the cloud layer into more or less horizontal bands of various colors.

Swirling storms exist on other planets, too, such as on Saturn and Neptune. Studying the atmospheric behavior of other planets may give us added insight into the workings of our own atmosphere. (Additional information about size, surface temperature, and atmospheric composition of planets is given in ▼ Table 1.)

▼ **TABLE 1** **Data on Planets and the Sun**

	DIAMETER (kilometers)	AVERAGE DISTANCE FROM SUN (millions of kilometers)	AVERAGE SURFACE TEMPERATURE*		MAIN ATMOSPHERIC COMPONENTS
			(°C)	(°F)	
Sun	1,392 × 103		5,800	10,500	—
Mercury	4,880	58	170	340	—
Venus	12,112	108	460	860	CO_2
Earth	12,742	150	15	59	N_2, O_2
Mars	6,800	228	−60	−76	CO_2
Jupiter	143,000	778	−145	−234	H_2, He
Saturn	121,000	1,427	−180	−290	H_2, He
Uranus	51,800	2,869	−225	−375	H_2, CH_4
Neptune	49,000	4,498	−210	−346	N_2, CH_4

*For the giant planets made up mostly of gas (Jupiter, Saturn, Uranus, and Neptune), the average temperature at cloud-top level is used.

FOCUS ON AN OBSERVATION 1.3

The Radiosonde

The vertical distribution of temperature, pressure, and humidity up to an altitude of about 30 km (about 19 mi) has been measured for more than 80 years with an instrument called a **radiosonde**.* The modern radiosonde is a small, lightweight box equipped with weather instruments and a radio transmitter. It is attached to a cord that has a parachute and a gas-filled balloon tied tightly at the end (see ● Fig. 4). As the balloon rises, the attached radiosonde measures air temperature with a small electrical thermometer—a thermistor—located just outside the box. The radiosonde measures humidity electrically by sending an electric current across a carbon-coated plate. Air pressure is obtained by a small barometer located inside the box. All of this information is transmitted to the surface by radio. Here, a computer rapidly reconverts the various frequencies into values of temperature, pressure, and moisture. Special tracking equipment at the surface may also be used to provide a vertical profile of winds. Today's radiosondes are usually equipped with Global Positioning System (GPS) receivers that lead to highly accurate wind computations. (When winds are added, the observation is called a *rawinsonde*.) When plotted on a graph, the vertical distribution of temperature, humidity, and wind is called a *sounding*. Eventually, the balloon bursts and the radiosonde returns to Earth, its descent being slowed by its parachute.

At most sites, radiosondes are released twice a day, usually at the time that corresponds to midnight and noon in Greenwich, England. Extra radiosondes are sometimes released at more frequent intervals to help improve forecasts when conditions are particularly threatening. Releasing radiosondes is an expensive operation because many of the instruments are never retrieved, and many of those that are retrieved are often in poor working condition. To complement the radiosonde, modern satellites (using instruments that measure radiant energy, the distortion of GPS signals due to atmospheric effects, and other variables) are providing scientists with vertical temperature profiles in inaccessible regions.

*A radiosonde that is dropped by parachute from an air craft is called a *dropsonde*.

NOAA

● **FIGURE 4** The radiosonde with parachute and balloon.

From Fig. 1.11 notice that in the stratosphere, the air temperature begins to increase with height, producing a *temperature inversion*. The inversion region, along with the lower isothermal layer, tends to keep the vertical currents of the troposphere from spreading into the stratosphere. The inversion also tends to reduce the amount of vertical motion in the stratosphere itself; hence, it is a stratified layer.

The reason for the inversion in the stratosphere is that ozone plays a major part in heating the air at this altitude. Recall that ozone is important because it absorbs energetic ultraviolet (UV) solar energy. Some of this absorbed energy warms the stratosphere from below, which explains why there is an inversion. If ozone were not present, the air probably would become colder with height, as it does in the troposphere.

WEATHER WATCH

The air density in the mile-high city of Denver, Colorado, is normally about 15 percent less than the air density at sea level. As the air density decreases, the drag force on a baseball in flight also decreases. Because of this fact, a baseball hit at Denver's Coors Field will travel farther than one hit at sea level. Coors Field usually ranks near the top of the Major League Baseball list for home-run counts, even though its outfield is a few feet longer than average.

Notice also in Fig. 1.11 that the level of maximum ozone concentration is observed near 25 km (at middle latitudes), yet the stratospheric air temperature reaches a maximum near 50 km. The reason for this phenomenon is that the air at 50 km is less dense than at 25 km, and so the absorption of intense solar energy at 50 km raises the temperature of fewer molecules to a much greater degree. Moreover, much of the solar energy responsible for the heating is absorbed in the upper part of the stratosphere and, therefore, does not reach down to the level of ozone maximum. And due to the low air density, the transfer of energy downward from the upper stratosphere is quite slow.

Although the air temperature increases with height in the stratosphere, the air at an altitude of 30 km (about 100,000 feet or 19 mi) is extremely cold, averaging less than −46°C (−51°F). At this level above polar latitudes, air temperatures can change dramatically from one week to the next. A phenomenon called a *sudden stratospheric warming* can raise the temperature in one week by more than 50°C. This rapid warming, although not fully understood, appears to be caused by energy propagating up from lower altitudes and disturbing the pool of cold air that is usually present in the lower stratosphere from late autumn to early spring. A sudden stratospheric warming can affect weather patterns for weeks over large areas.

WEATHER WATCH

Even without an engine, a human-piloted glider can soar to incredible heights. Such a glider is typically towed aloft by an aircraft and then gains more altitude by positioning itself where air is rising. A new world height record was achieved by the Perlan 2 glider in Argentina in September 2018 as it reached a height in the middle stratosphere of 76,124 feet (23,202 meters or about 23 km). Given that a human could not survive at such heights without oxygen, high-altitude gliders include systems that provide oxygen to pilots as needed.

Above the stratosphere is the **mesosphere** (middle sphere). The boundary near 50 km, which separates these layers, is called the *stratopause*. The air at this level is extremely thin and the atmospheric pressure is quite low, averaging about 1 mb, which means that only one-thousandth of all the atmosphere's molecules are above this level and 99.9 percent of the atmosphere's mass is located below it.

The percentage of nitrogen and oxygen in the mesosphere is about the same as at sea level. However, given the air's low density in this region, we would not survive breathing this air for very long. Here, each breath of air would contain far fewer oxygen molecules than it would near Earth's surface. Consequently, without proper breathing equipment, the brain would soon become oxygen-starved—a condition known as *hypoxia*. Pilots who fly above 3 km (10,000 ft) for too long without oxygen-breathing apparatus may experience this. With the first symptoms of hypoxia, there is usually no pain involved, just a feeling of exhaustion. Soon, visual impairment sets in and routine tasks become difficult to perform. Some people drift into an incoherent state, neither realizing nor caring what is happening to them. Of course, if this oxygen deficiency persists, a person will lapse into unconsciousness, and death may result. In fact, in the mesosphere, we would suffocate in a matter of minutes.

Other dire effects could be experienced in the mesosphere. Exposure to ultraviolet solar energy, for example, could cause severe burns on exposed parts of the body. Also, given the low air pressure, the blood in one's veins would begin to boil at normal body temperature.

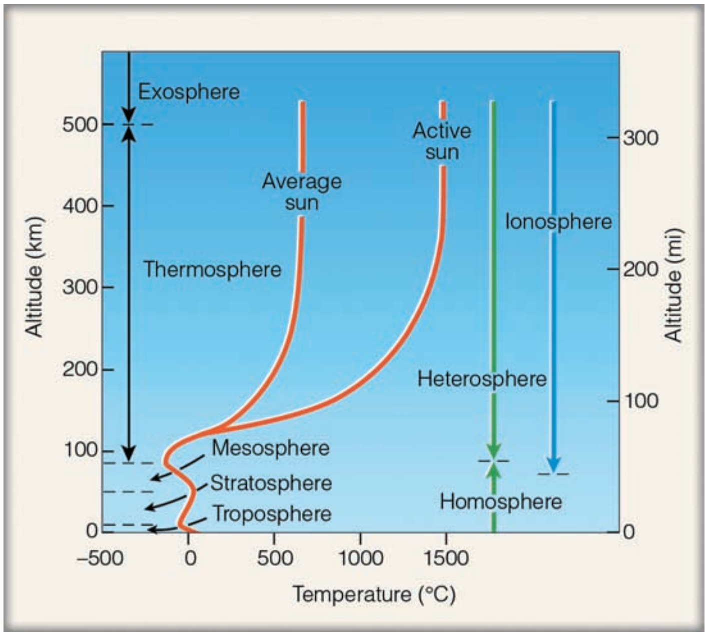
The air temperature in the mesosphere decreases with height, a phenomenon due, in part, to the fact that there is little ozone in the air to absorb solar radiation. Consequently, the molecules (especially those near the top of the mesosphere) are able to lose more energy than they absorb, which results in an energy deficit and cooling. So we find air in the mesosphere becoming colder with height up to an elevation near 85 km (53 mi). At this altitude, the temperature of the atmosphere reaches its lowest average value, −90°C (−130°F).

The "hot layer" above the mesosphere is the **thermosphere**. The boundary that separates the lower, colder mesosphere from the warmer thermosphere is the *mesopause*. In the thermosphere, oxygen molecules (O_2) absorb energetic solar rays, warming the air. Because there are relatively few atoms and molecules in the thermosphere, the absorption of a small amount of energetic solar energy can cause a large increase in air temperature. Furthermore, because the amount of solar energy affecting this region depends strongly on solar activity, temperatures in the thermosphere vary from day to day (see ● Fig. 1.13). The low density of the thermosphere also means that an air molecule will move an average distance (called *mean free path*) of over one kilometer before colliding with another molecule. A similar air molecule at Earth's surface will move an average distance of less than one millionth of a centimeter before it collides with another molecule. Moreover, it is in the thermosphere where charged particles from the sun interact with air molecules to produce dazzling aurora displays. (We will look at the aurora in more detail in Chapter 2.)

Because the air density in the upper thermosphere is so low, air temperatures there are not measured directly. They can, however, be determined by observing the orbital change of satellites caused by the drag of the atmosphere. Even though the air is extremely tenuous, enough air molecules strike a satellite to slow it down, making it drop into a slightly lower orbit. (Many spacecraft have fallen to Earth for this reason.) The amount of drag is related to the density of the air, and the density is related to the temperature. Therefore, by determining air density, scientists are able to construct a vertical profile of air temperature as illustrated in Fig. 1.13.

At the top of the thermosphere, about 500 km (300 mi) above Earth's surface, many of the lighter, faster-moving molecules traveling in the right direction actually escape Earth's gravitational pull. The region where atoms and molecules shoot off into space is sometimes referred to as the **exosphere**, which represents the upper limit of our atmosphere.

Up to this point, we have examined the atmospheric layers based on the vertical profile of temperature. The atmosphere, however, can also be divided into layers based on its



● **FIGURE 1.13** Layers of the atmosphere based on temperature (red line), composition (green line), and electrical properties (dark blue line). (An active sun is associated with large numbers of solar eruptions.)

composition. For example, the composition of the atmosphere begins to slowly change in the lower part of the thermosphere. Below the thermosphere, the composition of air remains fairly uniform (78 percent nitrogen, 21 percent oxygen) by turbulent mixing. This lower, well-mixed region is known as the **homosphere** (see Fig. 1.13). In the thermosphere, collisions between atoms and molecules are infrequent, and the air is unable to keep itself stirred. As a result, diffusion takes over as heavier atoms and molecules (such as oxygen and nitrogen) tend to settle to the bottom of the layer, while lighter gases (such as hydrogen and helium) float to the top. The region from about the base of the thermosphere to the top of the atmosphere is often called the **heterosphere**.

1.3c THE IONOSPHERE

The **ionosphere** is not really a layer, but rather an electrified region within the upper atmosphere where fairly large concentrations of ions and free electrons exist. *Ions* are atoms and molecules that have lost (or gained) one or more electrons. Atoms lose electrons and become positively charged when they cannot absorb all of the energy transferred to them by a colliding energetic particle or the sun's energy.

The lower region of the ionosphere is usually about 60 km (37 mi) above Earth's surface. From here (60 km), the ionosphere extends upward to the top of the atmosphere. Hence, as we can see in Fig. 1.13, the bulk of the ionosphere is in the thermosphere. Although the ionosphere allows TV and FM radio waves to pass on through, at night it reflects standard AM radio waves back to Earth. This situation allows AM radio waves to bounce repeatedly off the lower ionosphere and travel great distances.

BRIEF REVIEW

We have, in the last several sections, been examining our atmosphere from a vertical perspective. Following are a few of the main points:

- Atmospheric pressure at any level represents the total mass of air above that level, and atmospheric pressure always decreases with increasing height above the surface.
- The rate at which the air temperature decreases with height is called the lapse rate. An increase in air temperature with height is called an inversion.
- The atmosphere may be divided into layers (or regions) according to its vertical profile of temperature, its gaseous composition, or its electrical properties.
- The warmest atmospheric layer is the thermosphere; the coldest is the mesosphere. Most of the gas ozone is found in the stratosphere.
- We live at the bottom of the troposphere, an atmospheric layer where the air temperature normally decreases with height. The troposphere contains all of the weather with which we are familiar.
- The ionosphere is an electrified region of the upper atmosphere that normally extends from about 60 km to the top of the atmosphere.

Having looked at the composition of the atmosphere and its vertical structure, we will now turn our attention to weather events that take place in the lower atmosphere. As you read the remainder of this chapter, keep in mind that the content serves as a broad overview of material to come in later chapters, and that many of the concepts and ideas you encounter are designed to familiarize you with items you might see on TV or other electronic media, or read about on a website or in a newspaper or magazine.

1.4 Weather and Climate

LO6 LO7 LO8

When we talk about the **weather**, we are talking about the condition of the atmosphere at any particular time and place. Weather—which is always changing—includes the elements of:

1. *air temperature*—the degree of hotness or coldness of the air
2. *air pressure*—the force of the air above an area
3. *humidity*—a measure of the amount of water vapor in the air
4. *clouds*—visible masses of tiny water droplets and/or ice crystals that are above Earth's surface
5. *precipitation*—any form of water, either liquid or solid (rain or snow), that falls from clouds and reaches the ground
6. *visibility*—the greatest distance one can see
7. *wind*—the horizontal movement of air

If we measure and observe these *weather elements* over a specified interval of time, say, for many years, we would obtain the "average weather" or the **climate** of a particular region. Climate, therefore, represents the accumulation of daily and seasonal weather events (the average range of weather) over a long period of time. The concept of climate is much more than this, for it also includes the extremes of weather—the heat waves of summer and the cold spells of winter—that occur in a particular region. The *frequency* of these extremes is what helps us distinguish among climates that have similar averages.

If we were able to watch Earth for many thousands of years, even the climate would change. We would see rivers of ice moving down stream-cut valleys and huge glaciers—sheets of moving snow and ice—spreading their icy fingers over large portions of North America. Advancing slowly from Canada, a single glacier might extend as far south as Kansas and Illinois, with ice several thousands of meters thick covering the region now occupied by Chicago. Over an interval of two million years or so, we would see the ice advance and retreat many times. Of course, for this phenomenon to happen, the average temperature of North America would have to decrease and then rise in a cyclic manner.

Suppose we could photograph Earth once every thousand years for many hundreds of millions of years. In time-lapse film sequence, these photos would show that not only is the climate altering, but the whole Earth itself is changing as well: Mountains would rise up only to be torn down by erosion; isolated puffs of smoke and steam would appear as volcanoes spew hot gases and fine dust into the atmosphere; and the entire surface of Earth would undergo a gradual transformation as some ocean basins widen and others shrink.* The global climate change now in progress as a result of human-produced greenhouse gases is the most recent of these many long-term climate changes.

In summary, Earth and its atmosphere are dynamic systems that are constantly changing. While major transformations of Earth's surface are completed only after long spans of time, the state of the atmosphere can change in a matter of minutes. Hence, a watchful eye turned skyward will be able to observe many of these changes.

Up to this point, we have looked at the concepts of weather and climate without discussing the word *meteorology*. What does this term actually mean, and where did it originate?

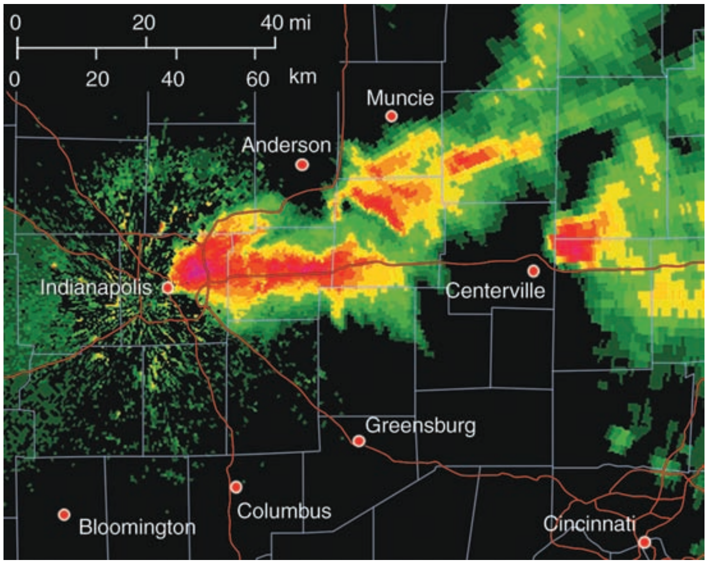
1.4a METEOROLOGY—A BRIEF HISTORY

Meteorology is the study of the atmosphere and its phenomena. The term itself goes back to the Greek philosopher Aristotle who, about 340 B.C.E., wrote a book on natural philosophy titled *Meteorologica*. This work represented the sum of knowledge on weather and climate at that time, as well as material on astronomy, geography, and chemistry. Some of the topics covered included clouds, rain, snow, wind, hail, thunder, and hurricanes. In those days, all substances that fell from the sky, and anything seen in the air, were called meteors, hence the term *meteorology*, which actually comes from the Greek word *meteoros*, meaning "high in the air." Today, we differentiate between those meteors that come from extraterrestrial sources outside our atmosphere (meteoroids) and particles of water and ice observed in the atmosphere (hydrometeors).

In *Meteorologica*, Aristotle attempted to explain atmospheric phenomena in a philosophical and speculative manner. Even though many of his ideas were found to be erroneous, Aristotle's work remained a dominant influence in the field of meteorology for almost two thousand years. In fact, the birth of meteorology as a genuine natural science did not take place until the invention of weather instruments during the Renaissance, such as the hygrometer in the mid-1400s, the thermometer in the late 1500s, and the barometer (for measuring air pressure) in the mid-1600s. With the newly available observations from instruments, attempts were then made to explain certain weather phenomena through scientific experimentation and the physical laws that were being developed at the time.

As more and better instruments were developed in the 1800s, the science of meteorology progressed. The invention of the telegraph in 1843 allowed for the transmission of routine weather observations. The understanding of the concepts of wind flow and storm movement became clearer, and in 1869 crude weather maps with *isobars* (lines of equal pressure) were drawn. Around 1920, the concepts of air masses and weather fronts were formulated in Norway. By the 1940s, daily upper-air balloon observations of temperature, humidity, and pressure gave a three-dimensional view of the atmosphere, and high-flying military aircraft discovered the existence of jet streams.

*The movement of the ocean floor and continents is explained in the theory of *plate tectonics*.



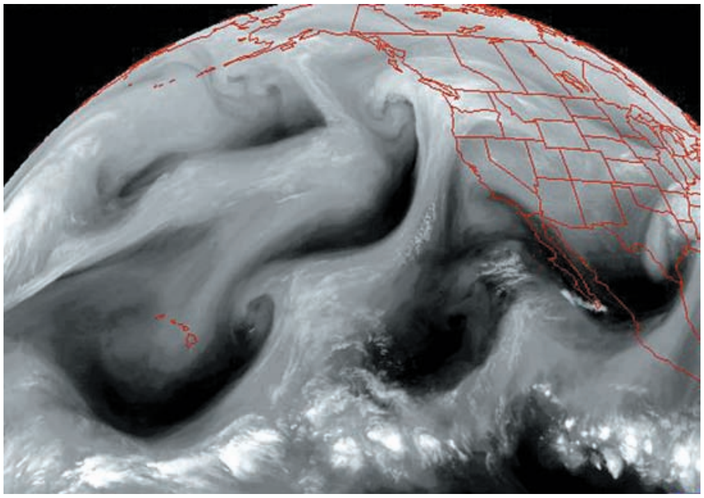
● **FIGURE 1.14** Doppler radar image showing precipitation over portions of Indiana. The areas shaded light green indicate lighter rain, whereas yellow indicates heavier rain. The dark red shaded areas represent the heaviest rain and the possibility of hail and intense thunderstorms.

CRITICAL THINKING QUESTION **Weather tends to move from west to east. Knowing this fact, explain why people living in Centerville would probably not be concerned about the thunderstorm just to the right of town in ● Fig. 1.14, but very concerned about the large intense thunderstorm (large red and yellow region) just east of Indianapolis. If this intense thunderstorm is moving toward Centerville at 40 mi/hr, about how long will it take the region of hail (light purple shade just east of Indianapolis) to reach Centerville, assuming the storm is able to hold together?**

Meteorology took another step forward in the 1950s, when scientists converted the mathematical equations that describe the behavior of the atmosphere into software called *numerical models* that could be run on new high-speed computers. These calculations were the beginning of *numerical weather prediction*. Today, computers plot the observations, draw the lines on the map, and forecast the state of the atmosphere for some desired time in the future. Meteorologists evaluate the results from various numerical models and use them to issue public forecasts.

After World War II, surplus military radars became available, and many were transformed into a national network of precipitation-measuring tools. In the mid-1990s, the National Weather Service replaced these original radars with the more sophisticated *Doppler radars*, which have the ability to peer into a severe thunderstorm and unveil its winds, as well as to show precipitation intensity (see ● Fig. 1.14). Recent upgrades to these Doppler radars make it possible for them to distinguish raindrops, snowflakes, hailstones, and even debris churned up by tornadoes.

In 1960, the first weather satellite, *Tiros I*, was launched by the United States, ushering in space-age meteorology. Subsequent satellites provided a wide range of useful information, ranging from time-lapse images of clouds and storms to images that depict swirling ribbons of water vapor flowing around the globe, as shown in ● Fig. 1.15. Over the last several decades, even more sophisticated satellites have been developed. These



● **FIGURE 1.15** This satellite image shows the dynamic nature of the atmosphere as ribbons of water vapor (gray regions) swirl counterclockwise about huge storms over the North Pacific Ocean.

satellites are supplying forecasters and computers with a far greater network of data so that more accurate and detailed forecasts can be developed.

With this brief history of meteorology, we are now ready to observe weather events that occur at Earth's surface.

1.4b A SATELLITE'S VIEW OF THE WEATHER

A great deal of information about the weather can be obtained from a single satellite image. ● Fig. 1.16 shows a portion of the Pacific Ocean and the North American continent. The image was obtained from a *geostationary satellite* situated about 36,000 km (22,300 mi) above Earth. At this elevation, the satellite travels at the same rate as Earth spins, which allows it to remain positioned above the same spot so it can continuously monitor what is taking place beneath it.

The thin solid black lines running from north to south on the satellite image are called *meridians*, or lines of longitude. Because the zero meridian (or prime meridian) runs through Greenwich, England, the *longitude* of any place on Earth is simply how far east or west, in degrees, it is from the prime meridian. North America is west of Great Britain and most of the United States lies between 75°W and 125°W longitude.

The solid black lines that parallel the equator are called *parallels of latitude*. The latitude of any place is how far north or south, in degrees, it is from the equator. The latitude of the equator is 0°, whereas the latitude of the North Pole is 90°N and that of the South Pole is 90°S. Most of the United States is located between latitude 30°N and 50°N, a region commonly referred to as the northern **middle latitudes**.

Storms of All Sizes Probably the most prominent aspect of Fig. 1.16 are the white cloud masses of all shapes and sizes. The clouds appear white because sunlight is reflected back to space from their tops. The largest of the organized cloud masses are the sprawling storms. One such storm appears as an extensive band of clouds, over 2000 km long, west of the Great Lakes. Superimposed on the satellite image is the storm's center (indicated by the large red L) and its adjoining weather fronts in red, blue, and purple. This **middle-latitude cyclonic storm system** (or *extratropical cyclone*) forms outside the tropics and, in the Northern Hemisphere, has winds spinning counterclockwise about its center, which is over Minnesota.

A slightly smaller but more vigorous storm is located over the Pacific Ocean near latitude 12°N and longitude 116°. This tropical storm system, with its swirling band of rotating clouds and sustained surface winds of 65 knots* (74 mi/hr) or more, is known as a **hurricane**. The diameter of the hurricane, as measured by the presence of winds of at least 34 knots (39 mph), is about 800 km (500 mi). The tiny dot at its center is called the *eye*. Near the surface, in the eye, winds are light, skies are generally clear, and the atmospheric pressure is lowest. Around the eye, however, is an extensive region where heavy rain and high surface winds are reaching peak gusts of 100 knots.

Smaller storms are seen as white spots over the Gulf of Mexico. These spots represent clusters of towering *cumulus* clouds that have grown into **thunderstorms**, that is, tall churning clouds accompanied by lightning, thunder, strong gusty winds, and heavy rain. If you look closely at Fig. 1.16, you will see similar cloud forms in many regions. There are probably more than a thousand thunderstorms occurring throughout the world at any moment, including this one. Although they cannot be seen individually, there are even some thunderstorms embedded in the cloud mass west of the Great Lakes. Later in the day on which this image was taken, a few of these storms spawned the most violent disturbance in the atmosphere: **tornadoes**.

A tornado is an intense rotating column of air that extends downward from the base of a thunderstorm with a circulation reaching the ground. Sometimes called *twisters*, or *cyclones*, they may appear as ropes or as large circular cylindera. They can be more than 2 km (1.2 mi) in diameter, although most are less than a football field wide. The majority of tornadoes have sustained winds below 100 knots, but some can pack winds exceeding 200 knots. Sometimes a visibly rotating funnel cloud dips part of the way down from a thunderstorm, then rises without ever forming a tornado.

A Glimpse at a Weather Map We can obtain a better picture of the middle-latitude storm system by examining a simplified surface weather map for the same day that the satellite image was taken. The weight of the air above different regions varies and, hence, so does the atmospheric pressure. In ● Fig. 1.17, the red letter L on the map indicates a region of low atmospheric pressure, often called a *low*, which marks the center of the middle-latitude storm. (Compare the center of the storm in Fig. 1.17 with that in Fig. 1.16.) The two blue letters H on the map represent regions of high atmospheric pressure, called *highs*, or *anticyclones*. The circles on the map represent either individual weather stations or cities where observations are taken. The **wind** is the horizontal movement of air. The **wind direction**—the direction *from which* the wind is blowing**—is given by

*Recall from p. 13 that 1 knot equals 1.15 miles per hour.

**If you are facing north and the wind is blowing on your face, the wind would be called a "north wind."

wind barbs, lines that parallel the wind and extend outward from the center of the station. The **wind speed**—the rate at which the air is moving past a stationary observer—is indicated by *flags*, the short lines that extend off each wind barb.

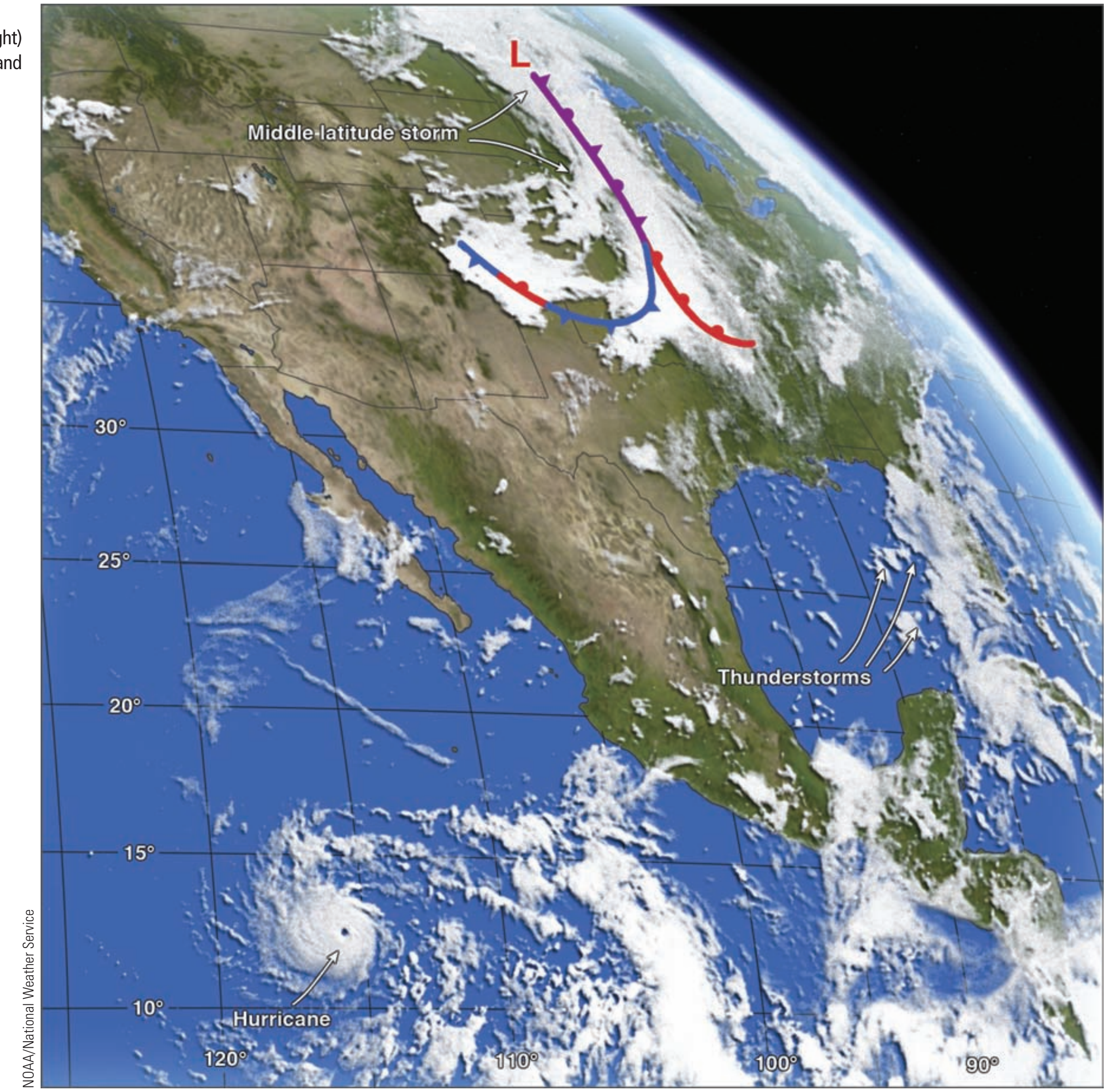
Notice how the wind blows around the highs and the lows. The horizontal pressure differences create a force that starts the air moving from higher pressure toward lower pressure. Because of Earth's rotation, the winds are deflected from their path toward the right in the Northern Hemisphere.* This deflection causes the winds to blow *clockwise* and *outward* from the center of the highs, and *counterclockwise* and *inward* toward the center of the low.

As the surface air spins into the low, it flows together and is forced upward, like toothpaste squeezed out of an upward-pointing tube. The rising air cools, and the water vapor in the air condenses into clouds. Notice on the weather map that the area of precipitation (the shaded green area) in the vicinity of the low corresponds to an extensive cloudy region in the satellite image (Fig. 1.16).

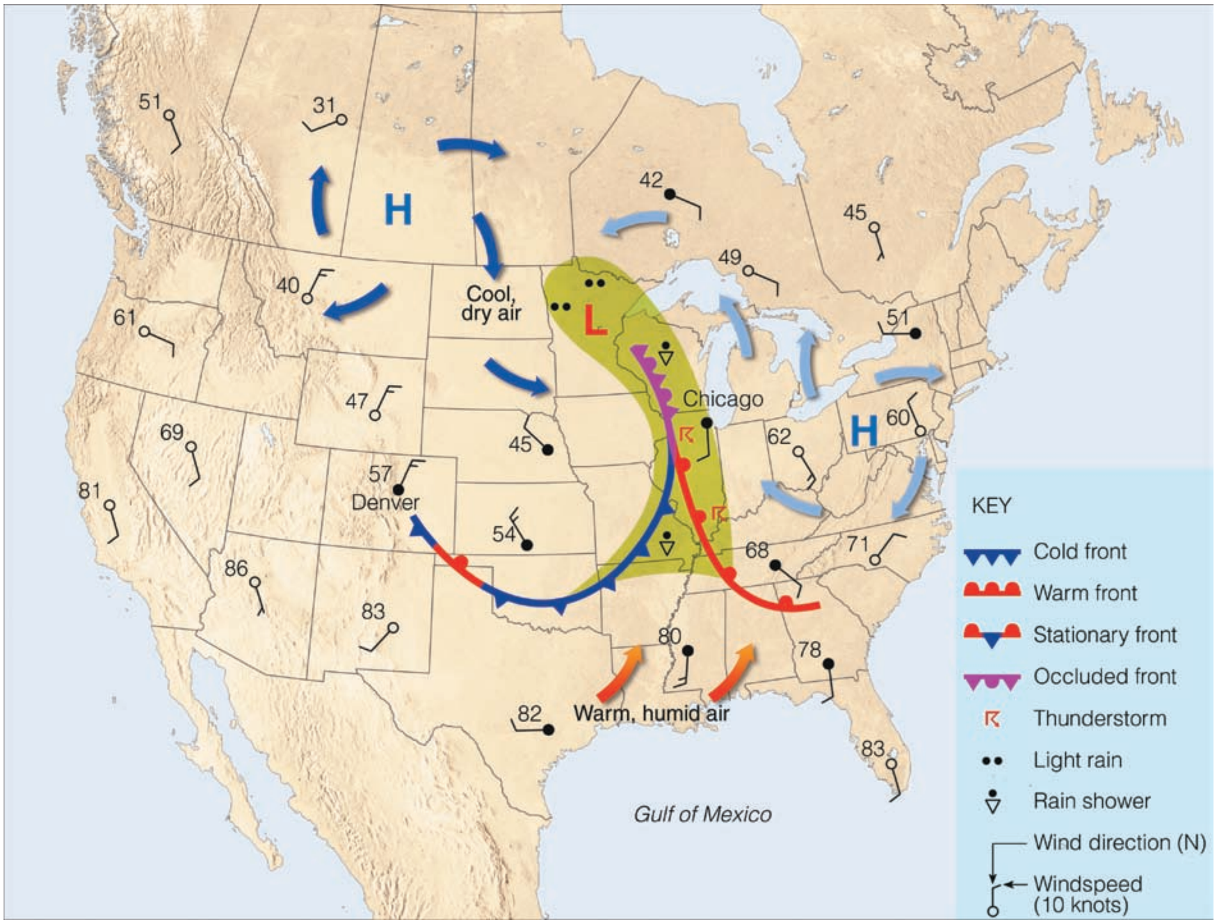
Also notice by comparing Figs. 1.16 and 1.17 that, in the regions of high pressure, skies are generally clear. As the surface air flows outward away from the center of a high, air sinking from above must replace the laterally spreading surface air. Because sinking air does not usually produce clouds, we find generally clear skies and fair weather associated with the regions of high atmospheric pressure.

Areas of high and low pressure, and the swirling air around them, are the major weather producers for the middle latitudes. Look at the middle-latitude storm and the surface temperatures in Fig. 1.17 and notice that, to the southeast of the storm, southerly winds from the Gulf of Mexico are bringing warm, humid air northward over much of the southeastern portion of the nation. On the storm's western side, cool, dry northerly breezes combine with sinking air to create generally clear weather over

*This deflecting force, known as the *Coriolis force*, is discussed more completely in Chapter 8, as are the winds.



● **FIGURE 1.16** This satellite image (taken in visible reflected light) shows a variety of cloud patterns and storms in Earth's atmosphere.



● **FIGURE 1.17** Simplified surface weather map that correlates with the satellite image shown in Fig. 1.16. The shaded green area represents precipitation. The numbers on the map represent air temperatures in °F. Because this map shows conditions several hours after those in Figure 1.16, the frontal system across the Midwest is farther east.

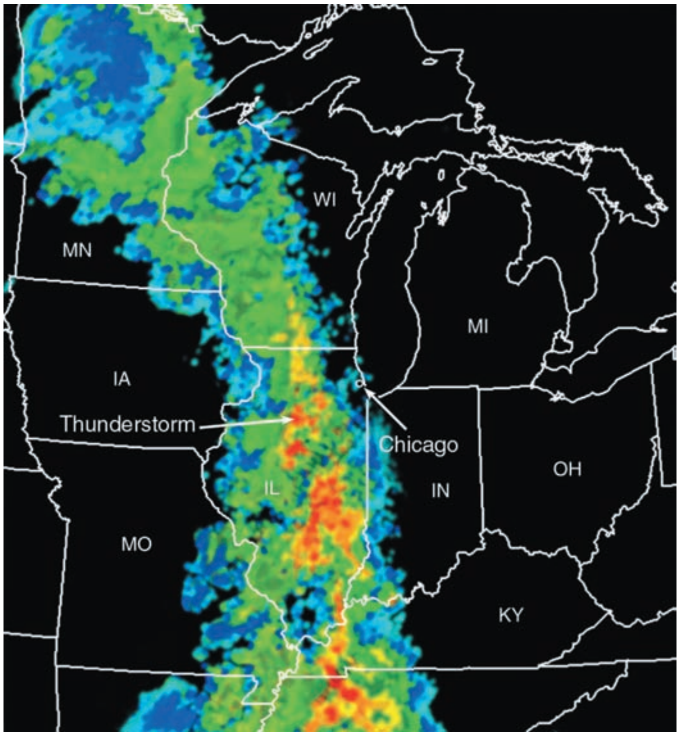
the Rocky Mountains. The boundary that separates the warm and cool air appears as a heavy, colored line on the map—a **front**, across which there is a sharp change in temperature, humidity, and wind direction.

Where the cool air from Canada replaces the warmer air from the Gulf of Mexico, a *cold front* is drawn in blue, with arrowheads showing the front's general direction of movement. Where the warm Gulf air is replacing cooler air to the north, over the Midwest, a *warm front* is drawn in red, with half circles showing its general direction of movement. Where the cool air over the Midwest is being displaced by colder air from Canada, an *occluded front* is drawn in purple, with alternating arrowheads and half circles to show how it is moving. Along each of the fronts, warm air is rising, producing clouds and precipitation. Notice in the satellite image (Fig. 1.16) that the occluded front and the cold front appear as an elongated, curling cloud band that stretches from the low-pressure area over Minnesota into the northern part of Texas.

Notice in Fig. 1.17 that the frontal system is to the west of Chicago. As the westerly winds aloft push the front eastward, a person on the outskirts of Chicago might observe the approaching front as a line of towering thunderstorms similar to those in ● Fig. 1.18. On a Doppler radar image, the advancing thunderstorms might appear similar to those shown in ● Fig. 1.19. In a few hours, Chicago should experience heavy showers with thunder, lightning, and gusty winds as the front passes. All of this, however, should give way to clearing skies and surface winds from the west or northwest after the front has moved on.

Courtesy of Robert Henson

● **FIGURE 1.18** Thunderstorms developing and advancing along an approaching cold front.



● **FIGURE 1.19** An elongated frontal system can show up on Doppler radar as a line of different colors. In this composite image, the areas shaded green and blue indicate where light-to-moderate rain is falling. Yellow indicates heavier rainfall. The red-shaded area represents the heaviest rainfall and the possibility of intense thunderstorms. Notice that a thunderstorm is approaching Chicago from the west.

Observing storm systems, we see that not only do they move but they constantly change. Steered by the upper-level westerly winds, the middle-latitude storm in Fig. 1.17 gradually weakens and moves eastward, carrying its clouds and weather with it. In advance of this system, a sunny day in Ohio will gradually cloud over and transition to heavy showers and thunderstorms by nightfall. Behind the storm, cool, dry northerly winds rushing into eastern Colorado cause an overcast sky to give way to clearing conditions. Farther south, the thunderstorms over the Gulf of Mexico in the satellite image (Fig. 1.16) expand a little, then dissipate as new storms appear over water and land areas. To the west, the hurricane over the Pacific Ocean drifts northwestward and encounters cooler water. Here, away from its warm energy source, it loses its punch; winds taper off, and the storm soon turns into a disorganized mass of clouds and tropical moisture.

1.4c WEATHER AND CLIMATE IN OUR LIVES

Weather and climate play a major role in our lives. Weather, for example, often dictates which clothes we wear on a given day, while climate influences the range of clothing we keep in our wardrobe. Climate determines when to plant crops as well as what type of crops can be planted. Weather determines if these same crops will grow to maturity. Although weather and climate affect our lives in many ways, perhaps their most immediate effect is on our comfort. In order to survive the cold of winter and heat of summer, we build homes, heat them, air-condition them, and insulate them—only to find that when we leave our shelter, we are still at the mercy of the weather elements.

WEATHER WATCH

Weather influences our bank accounts as well as our mood and our safety. From 1980 to 2019, the United States experienced more than 250 disasters that each cost more than $1 billion (adjusted for inflation), according to the National Oceanic and Atmospheric Administration. More than half of these losses—close to a trillion dollars (2019 USD)—were related to hurricanes and tropical storms. The runner-up, drought, took an economic toll of more than $240 billion.

Even when we are dressed for the weather properly, wind, humidity, and precipitation can change our perception of how cold or warm it feels. On a cold, windy day, the effects of *wind chill* tell us that it feels much colder than it really is, and, if not properly dressed, we run the risk of *frostbite* or even *hypothermia* (the rapid, progressive mental and physical collapse that accompanies the lowering of human body temperature). On a hot, humid day we normally feel uncomfortably warm and blame it on the humidity. If we become too warm, our bodies overheat and *heat exhaustion* or *heat stroke* may result. Those most likely to suffer these maladies are the elderly with impaired circulatory systems and infants, whose heat-regulating mechanisms are not yet fully developed.

Weather affects how we feel in other ways, too, not all of them well understood. People with arthritis often report more pain when atmospheric moisture is increasing rapidly, or when atmospheric pressure is changing abruptly. Heart attacks become more likely when the temperature decreases, perhaps because our blood thickens and blood vessels constrict. The risk of heart attack and stroke also rises during periods of stagnant, polluted air, as we inhale tiny particles that enter our bloodstream. People who are light-sensitive may experience more headaches on bright, sunny days. Some people who live near mountainous regions become irritable or depressed during a warm, dry wind blowing downslope (a *chinook wind*).

When the weather turns much colder or warmer than normal, it has direct impacts on the lives and pocketbooks of many people. For example, the exceptionally warm weather observed from January to March 2012 over the United States saved people millions of dollars in heating costs. On the other side of the coin, the colder-than-normal winters of 2013–2014 and 2014–2015 over much of the northeastern United States sent utility costs soaring as demand for heating fuel escalated.

Major cold spells accompanied by heavy snow and ice can play havoc by snarling commuter traffic, curtailing airport services, closing schools, and downing power lines, thereby cutting off electricity to thousands of customers (see ● Fig. 1.20). For example, a huge ice storm during January 1998 in northern New England and Canada left millions of people without power and caused over a billion dollars in damages, and a devastating snowstorm during February 2011 produced blizzard conditions from Oklahoma to Michigan and snow drifts of up to 15 feet in the Chicago area. When frigid air settles into the Deep South, many millions of dollars' worth of temperature-sensitive fruits and vegetables may be ruined, the eventual consequence being higher produce prices for consumers.

● **FIGURE 1.20** Utility workers in Maine clear off broken tree branches from power lines during a major ice storm on December 12, 2008.

Prolonged drought, especially when accompanied by high temperatures, can lead to a shortage of food and, in some places, widespread starvation. Parts of Africa, for example, have periodically suffered through major droughts and famine. During the summer of 2012, much of the United States experienced a severe drought with searing summer temperatures and wilting crops, causing billions of dollars in crop losses. California experienced an especially destructive drought from 2011 to 2016. When the climate turns hot and dry, animals suffer too. As many as 6000 cattle perished during a California heat wave in June 2017. Severe drought also has an effect on water reserves, often forcing communities to ration water and restrict its use. During periods of extended drought, vegetation often becomes tinder-dry, and, sparked by lightning or a careless human, such a dried-up region can quickly become a raging inferno. California experienced a devastating sequence of fires in 2017 and 2018 that together killed more than 100 people and destroyed more than 28,000 structures (see ● Fig. 1.21).

Every summer, scorching *heat waves* take many lives. From 2009 to 2018, an annual average of more than 100 deaths in the United States were attributed to excessive heat exposure. In one particularly devastating heat wave that hit Chicago, Illinois, during July 1995, high temperatures coupled with high humidity claimed the lives of more than 700 people. Heat waves have been especially devastating in recent years in South and Southeast Asia, where millions of outdoor workers are at risk, and across Europe, where many cities and buildings are not designed for intense heat. In the summer of 2003, tens of thousands died across Europe, including 14,000 in France alone. A record-breaking heat wave in Russia in 2010 killed nearly 11,000 people in Moscow. Another intense pair of heat waves struck western Europe in 2019, but the death toll was much reduced this time, as Paris and other cities had adopted measures to increase public safety during extreme heat.

Every year, the violent side of weather influences the lives of millions. Those who live along the U.S. Gulf and Atlantic coastlines keep a close watch for hurricanes during the late summer and early autumn. These large tropical systems can be among the nation's most destructive weather events. More than 250,000 people lost their homes when Hurricane Andrew struck the Miami area in 1992, and nearly 2000 people along the Central Gulf Coast were killed by Hurricane Katrina in 2005. A late-season hurricane called Sandy took a rare path in October 2012, striking the mid-Atlantic coast from the southeast. Because of its vast size and unusual path, Sandy produced catastrophic storm-surge flooding and caused more than 100 deaths across parts of New Jersey, New York, and New England (see ● Fig 1.22). In 2017, three intense hurricanes—Harvey, Irma, and Maria—caused massive destruction and took dozens of lives in Texas, Florida, Puerto Rico, and other Caribbean islands. Another disastrous storm, Hurricane Michael, struck the Florida Panhandle in 2018.

● **FIGURE 1.21** A firefighter lights backfires during the Carr Fire in Redding, California on July 27, 2018. The fire destroyed more than 1600 structures, took eight lives, and burned 229,000 acres.

● **FIGURE 1.22** A resident of Long Beach, New York, digs sand out from around his car after Hurricane Sandy pushed water and sand far inland in October 2012, destroying homes, commercial businesses, and approximately 10,000 cars in this area alone.

Andrea Booher/FEMA

● **FIGURE 1.23** Lightning flashes inside a violent tornado that tore through Joplin, Missouri, on May 22, 2011. The tornado ripped through a hospital and destroyed entire neighborhoods. (See tornado damage in Fig. 1.24.)

AP Images/tornadovideo.net

● **FIGURE 1.24** Emergency personnel walk through a neighborhood in Joplin, Missouri, damaged by a violent tornado, with winds exceeding 174 knots (200 mi/hr), on May 22, 2011. The tornado caused hundreds of millions of dollars in damage and took 159 lives, making this single tornado the deadliest in the United States since 1947.

AP Images/Mark Schiefelbein

AP Images/David J. Phillip

● **FIGURE 1.25** Residents evacuate an apartment complex in the Houston area on April 18, 2016, as torrential rains from severe thunderstorms produced severe flash flooding. More than 1000 high-water rescues took place.

Although the gentle rains of a typical summer thunderstorm are welcome over much of North America, the heavy downpours, high winds, and large hail of the *severe thunderstorms* are not. *Tornadoes* spawned by severe thunderstorms not only take dozens of lives each year in the United States, but annually they cause damage to buildings and property totaling in the hundreds of millions of dollars, as a single large tornado can level an entire section of a town (see ● Figs. 1.23 and 1.24). Cloudbursts from intense, slow-moving thunderstorms can provide too much rain too quickly, creating *flash floods* as small streams become raging rivers composed of mud and sand entangled with uprooted plants and trees. Thunderstorms dumped up to 20 inches of rain in just a few hours over parts of the Houston area in April 2016, leading to severe flash flooding (see ● Fig. 1.25). If heavy rain covers a large area, devastating *river floods* can result. Record rainfall produced both flash floods and river floods over the Southern Plains in May 2015 and across South Carolina in October 2015. On average, more people die in the United States from flooding than from either lightning strikes or tornadoes.

Strong downdrafts originating inside an intense thunderstorm (a *downburst*) create turbulent winds that are capable of destroying crops and inflicting damage upon surface structures. Until a safety system implemented in the 1990s virtually eliminated such deaths, hundreds of people were killed in United States airline crashes attributed to turbulent *wind shear* (a rapid change in wind speed and/or wind direction) from downbursts. In a typical year, hail causes more than $1 billion in damage to crops and property in the United States, and lightning takes the lives of several dozen people and starts fires that destroy many thousands of acres of valuable timber (see ● Fig. 1.26).

Up to this point, we have considered the more violent side of weather and its impact on humanity. Weather- and climate-related events can have enormous economic consequences. On average, tens of billions of dollars in property damage occur each year in the United States alone. However, even the quiet side of weather has its influence. When winds die down and humid air becomes more tranquil, fog may form. Dense fog can restrict visibility at airports, causing flight delays and cancellations. Every winter, deadly fog-related auto accidents occur along our busy highways and turnpikes. But fog has a positive side, too, especially during a dry spell, as fog moisture collects on tree branches and drips to the ground, where it provides water for the tree's root system.

A. T. Willett/Alamy Stock Photo

● **FIGURE 1.26** Estimates are that lightning strikes Earth about 40 to 50 times every second. More than 20 million lightning strikes hit the United States in a typical year. Here, lightning strikes the ground and buildings over Phoenix, Arizona.

Weather and climate have become so much a part of our lives that the first thing many of us do in the morning is to consult our local weather forecast on our smartphone or on TV or radio. For this reason, most television stations and many larger radio stations have their own "weather person" to present weather information and give daily forecasts. More and more of these people are professionally trained in meteorology, and many stations require that the weathercaster be certified by the American

Meteorological Society (AMS) or hold a seal of approval from the National Weather Association (NWA). To make their weather presentation as up-to-the-minute as possible, weathercasters draw upon time-lapse satellite images, color Doppler radar displays, and other ways of illustrating current weather. Many stations work with private firms that create graphics and customized forecasts, largely based on observations and computer models from the National Weather Service (NWS). Since 1982, a staff of trained professionals at The Weather Channel have provided weather information 24 hours a day on cable television.

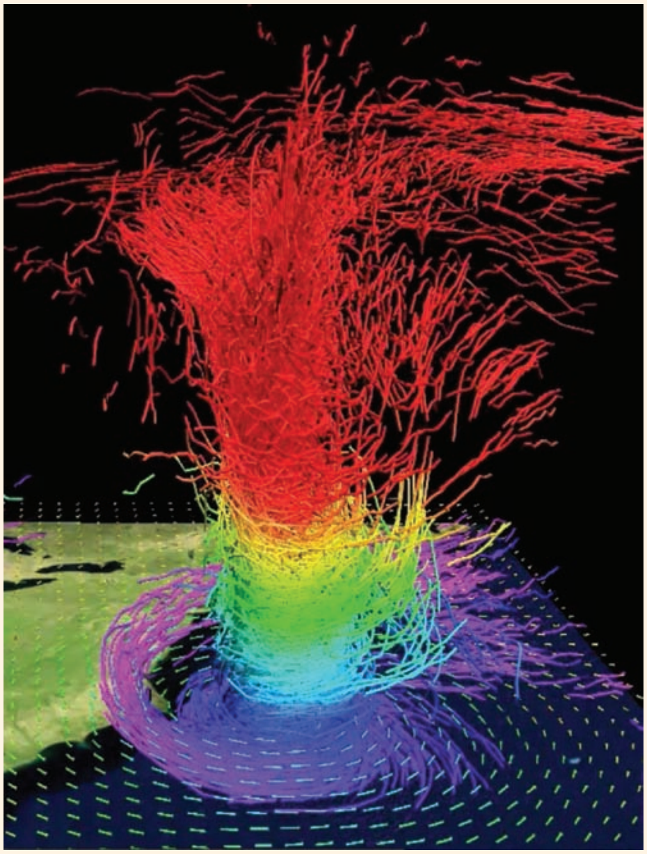
FOCUS ON A SPECIAL TOPIC 1.4

What Is a Meteorologist?

Most people associate the term "meteorologist" with the weatherperson they see on television or hear on the radio. Many television and radio weathercasters are in fact professional meteorologists, but some are not. A meteorologist uses scientific principles to explain and to forecast atmospheric phenomena. A professional meteorologist is usually considered to be a person who has completed the requirements for a college degree in meteorology or atmospheric science. This individual has strong, fundamental knowledge concerning how the atmosphere behaves, along with a substantial background of coursework in mathematics, physics, and chemistry. Many professional meteorologists are also adept at computer programming.

About half of the approximately 9000 meteorologists and atmospheric scientists in the United States are employed by the National Weather Service, the military, or private firms, including media outlets. The other half work mainly in research, teach atmospheric science courses in colleges and universities, or do meteorological consulting work.

Scientists who carry out atmospheric research may be investigating how the climate is changing, how snowflakes form, or how pollution impacts temperature patterns. Aided by supercomputers, much of the work of a research meteorologist involves simulating the atmosphere to see how it behaves (see ● Fig. 5). Researchers often work closely with such scientists as chemists, physicists, oceanographers, mathematicians, and environmental experts to determine how the atmosphere interacts with the entire ecosystem. Scientists doing work in physical meteorology may study how radiant energy warms the atmosphere at various locations or times; those at work in the field of dynamic meteorology might be using the mathematical equations that describe airflow to learn more about jet streams. Scientists working in operational meteorology might be involved with preparing a weather forecast by analyzing upper-air information over North America, or they may be improving the software used to produce automated weather predictions. A climatologist, or climate scientist, might be studying the interaction of the atmosphere and ocean to see what influence such interchange might have on planet Earth many years from now.


UCAR/Image courtesy Mel Shapiro

● **FIGURE 5** A three-dimensional model of Hurricane Sandy, which struck the New Jersey coast in October 2012 (see Figure 1.22). The model shows air at the surface flowing counterclockwise around the storm (arrows) and rising through it in a spiraling fashion. The height of the storm is greatly exaggerated to depict the airflow in more detail.

Meteorologists also provide a variety of services not only to the general public in the form of weather forecasts but also to city planners, contractors, farmers, and large corporations. Meteorologists working for private weather firms create many forecasts and graphics that are found in newspapers, on television, and on the Internet. Overall, there are many exciting jobs that fall under the heading of "meteorologist"—too many to mention here. For more information on this topic, visit http://www.ametsoc.org/ and click on "Education and Careers."

(Many viewers believe the weatherperson they see on TV is a meteorologist and that all meteorologists forecast the weather. If you are interested in learning what a meteorologist or atmospheric scientist is and what he or she might do for a living other than forecast the weather, read Focus section 1.4.)

The National Oceanic and Atmospheric Administration (NOAA), the parent agency of the National Weather Service, sponsors weather radio broadcasts at selected locations across the United States. Known as *NOAA Weather Radio* (and transmitted at VHF–FM frequencies), this service provides continuous weather information and regional forecasts (as well as special weather advisories, including watches and warnings) for over 90 percent of the United States.

Although millions of people rely on weather broadcasts on radio and TV, many millions use forecasts obtained on their smartphones or on personal computers. Smartphone applications can be tailored to provide conditions and forecasts for your hometown or wherever you may be traveling. Websites operated by the NWS and private forecasting companies provide a wealth of local, national, and global data and forecasts.

SUMMARY

This chapter provides an overview of Earth's atmosphere. Our atmosphere is one rich in nitrogen and oxygen as well as smaller amounts of other gases, such as water vapor, carbon dioxide, and other greenhouse gases whose increasing levels are resulting in additional global warming and climate change. We examined Earth's early atmosphere and found it to be much different from the air we breathe today.

We investigated the various layers of the atmosphere: the troposphere (the lowest layer), where almost all weather events occur, and the stratosphere, where ozone protects us from a portion of the sun's harmful rays. In the stratosphere, ozone undergoes a seasonal decrease over parts of the Northern and Southern Hemispheres related to human-produced chemicals. Above the stratosphere lies the mesosphere, where the air temperature drops dramatically with height. Above the mesosphere lies the warmest part of the atmosphere, the thermosphere. At the top of the thermosphere is the exosphere, where collisions between gas molecules and atoms are so infrequent that fast-moving lighter molecules can actually escape Earth's gravitational pull and shoot off into space. The ionosphere represents that portion of the upper atmosphere where large numbers of ions and free electrons exist.

We looked briefly at the weather map and a satellite image and observed that storms and clouds of all sizes and shapes are dispersed throughout the atmosphere. The movement, intensification, and weakening of these systems, as well as the dynamic nature of air itself, produce a variety of weather events that we described in terms of weather elements. The sum total of weather and its extremes over a long period of time is what we call climate. Although sudden changes in weather may occur in a moment, climatic change takes place gradually over many years. The study of the atmosphere and all of its related phenomena is called *meteorology*, a term whose origin dates back to the days of Aristotle. Finally, we discussed some of the many ways weather and climate influence our lives.

KEY TERMS

The following terms are listed (with corresponding page numbers) in the order they appear in the text. Define each. Doing so will aid you in reviewing the material covered in this chapter.

atmosphere, 4
outgassing, 5
nitrogen, 6
oxygen, 6
water vapor, 6
carbon dioxide, 8
ozone, 9
ozone hole, 10
aerosols, 10
pollutants, 10
density, 11
pressure, 12
air pressure, 12
lapse rate, 13
temperature inversion, 13
troposphere, 13
stratosphere, 13
tropopause, 13
radiosonde, 15
mesosphere, 16
thermosphere, 16
exosphere, 16
homosphere, 17
heterosphere, 17
ionosphere, 17
weather, 17
climate, 17
meteorology, 18
middle latitudes, 19
middle-latitude cyclonic storm system, 19
hurricane, 19
thunderstorms, 19
tornadoes, 19
wind, 19
wind direction, 19
wind speed, 20
front, 21

QUESTIONS FOR REVIEW

1. What is the primary source of energy for Earth's atmosphere?
2. List the four most abundant gases in today's atmosphere.
3. Of the four most abundant gases in our atmosphere, which one shows the greatest variation at Earth's surface?
4. What are some of the important roles that water plays in our atmosphere?
5. Briefly explain the production and natural destruction of carbon dioxide near Earth's surface. Give two reasons for the increase of carbon dioxide over the past 100-plus years.
6. List the two most abundant greenhouse gases in Earth's atmosphere. What makes them greenhouse gases?
7. Explain how the atmosphere "protects" inhabitants at Earth's surface.

8. What are some of the aerosols in our atmosphere?
9. How has the composition of Earth's atmosphere changed over time? Briefly outline the evolution of Earth's atmosphere.
10. (a) Explain the concept of air pressure in terms of mass of air above some level.
    (b) Why does air pressure always decrease with increasing height above the surface?
11. What is standard atmospheric pressure at sea level in
    (a) inches of mercury
    (b) millibars, and
    (c) hectopascals?
12. What is the average or standard temperature lapse rate in the troposphere?
13. Briefly describe how the air temperature changes from Earth's surface to the lower thermosphere.
14. On the basis of temperature, list the layers of the atmosphere from the lowest layer to the highest.
15. What atmospheric layer contains all of our weather?
16. In what atmospheric layer do we find
    (a) the lowest average air temperature?
    (b) the highest average temperature?
    (c) the highest concentration of ozone?
17. Above what region of the world would you find the ozone hole?
18. Why is it that without proper breathing apparatus, you would not be able to survive in the upper stratosphere, even though the concentration of oxygen there is similar to the concentration near ground level (about 21 percent by volume)?
19. Define *meteorology* and discuss the origin of this word.
20. When someone says that "the wind direction today is south," does this mean that the wind is blowing *toward the south or from the south?*
21. Describe at least six features observed on a surface weather map.
22. Explain how wind blows around low- and high-pressure areas in the Northern Hemisphere.
23. How are fronts defined?
24. Rank the following storms in size from largest to smallest: hurricane, tornado, middle-latitude cyclonic storm, thunderstorm.
25. Weather in the middle latitudes tends to move in what general direction?
26. How does weather differ from climate?
27. Describe at least seven ways weather and climate influence the lives of people.

QUESTIONS FOR THOUGHT

1. Which of the following statements relate more to weather and which relate more to climate?
    (a) The summers here are warm and humid.
    (b) Cumulus clouds are covering the entire sky.
    (c) Our lowest temperature last winter was −29°C (−18°F).
    (d) The air temperature outside is 22°C (72°F).
    (e) December is our foggiest month.
    (f) The highest temperature ever recorded in Phoenixville, Pennsylvania, was 44°C (111°F) on July 10, 1936.
    (g) Snow is falling at the rate of 5 cm (2 in.) per hour.
    (h) The average temperature for the month of January in Chicago, Illinois, is −3°C (26°F).
2. A standard pressure of 1013.25 millibars is also known as one atmosphere (1 atm).
    (a) Look at Fig. 1.10 and determine at approximately what levels you would record a pressure of 0.5 atm and 0.1 atm.
    (b) The surface air pressure on the planet Mars is about 0.007 atm. If you were standing on Mars, the surface air pressure would be equivalent to a pressure observed at approximately what altitude in Earth's atmosphere?
3. If you were suddenly placed at an altitude of 100 km (62 mi) above Earth, would you expect your stomach to expand or contract? Explain.
4. In ● Fig. 1.27 below below, what are at least two kinds of weather impacts that might be occurring at this location?

Scott Olson/Getty Images News/Getty Images

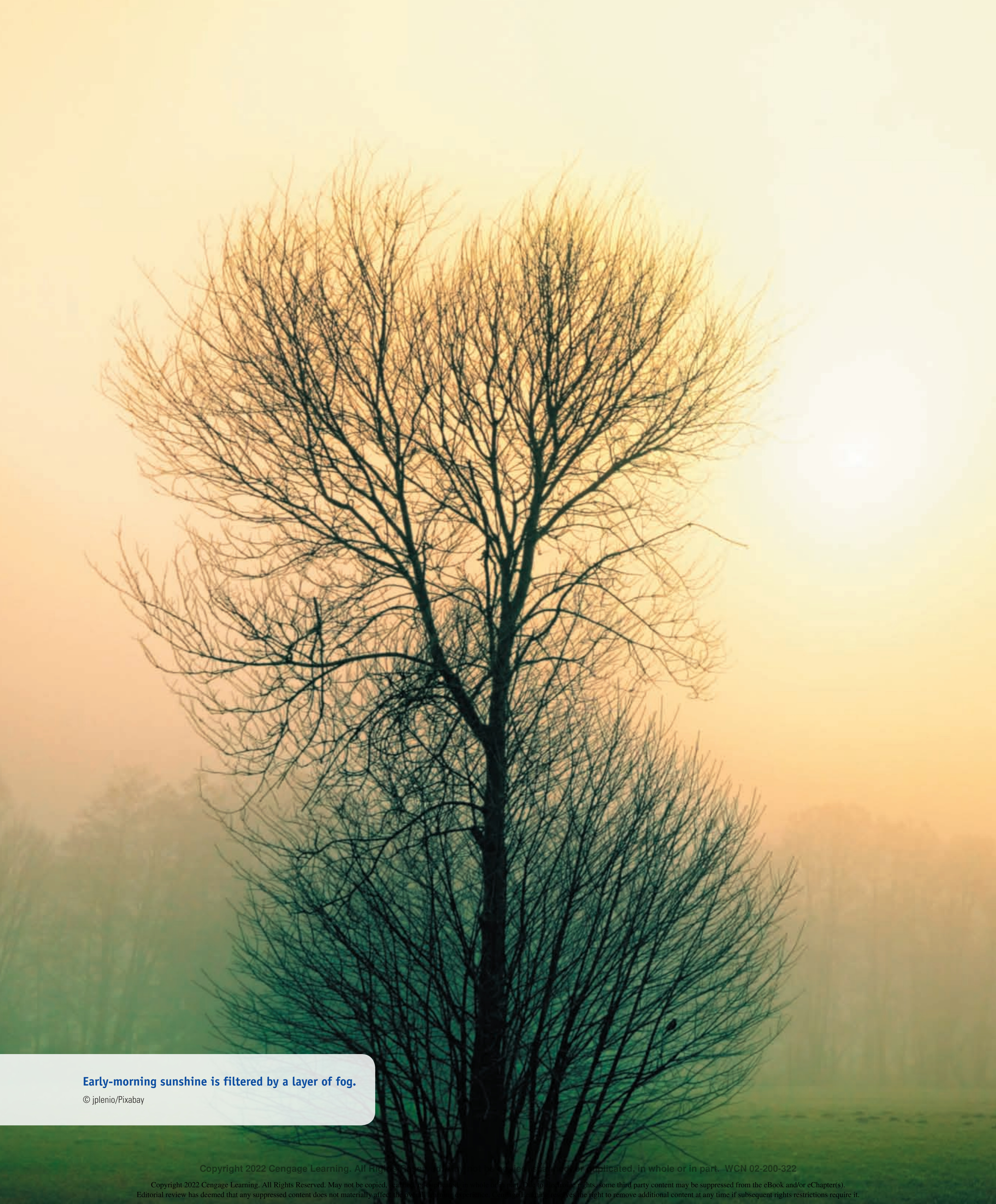
● **FIGURE 1.27**

PROBLEMS AND EXERCISES

1. Keep track of the weather. On an outline map of North America, mark the daily position of fronts and pressure systems for a period of several weeks or more. (This information can be obtained from the NOAA Daily Weather Map website, https://www.wpc.ncep.noaa.gov/dailywxmap, or other online sources.) Sketch the general upper-level flow pattern (found at the same website) atop the surface features. Observe how the surface systems move. Relate this information to the material on wind, fronts, and cyclones covered in later chapters.
2. Compose a one-week journal, including daily weather maps and weather forecasts for your location obtained from an app, a website, a newspaper, or a weathercast. Provide a commentary for each day regarding the correlation of actual and predicted weather.
3. Formulate a short-term climatology for your city for one month by recording maximum and minimum temperatures and precipitation amounts every day. You can get this information from websites (including http://nws.noaa.gov), television, newspapers, or your own measurements. Compare this data to the climatology for that month (the average from many years) at the nearest official observing site to your location. How can you explain any large differences between the two?
4. Suppose a friend poses a question about how weather systems generally move in the middle latitudes. He puts forth a hypothesis that these systems generally move from east to west. How would you use the scientific method to prove his hypothesis to be incorrect?

ONLINE RESOURCES

Visit www.cengage.com to view additional resources, including video exercises, online quizzes, an interactive eBook, and more.



Early-morning sunshine is filtered by a layer of fog.

© jplenio/Pixabay

CHAPTER 2

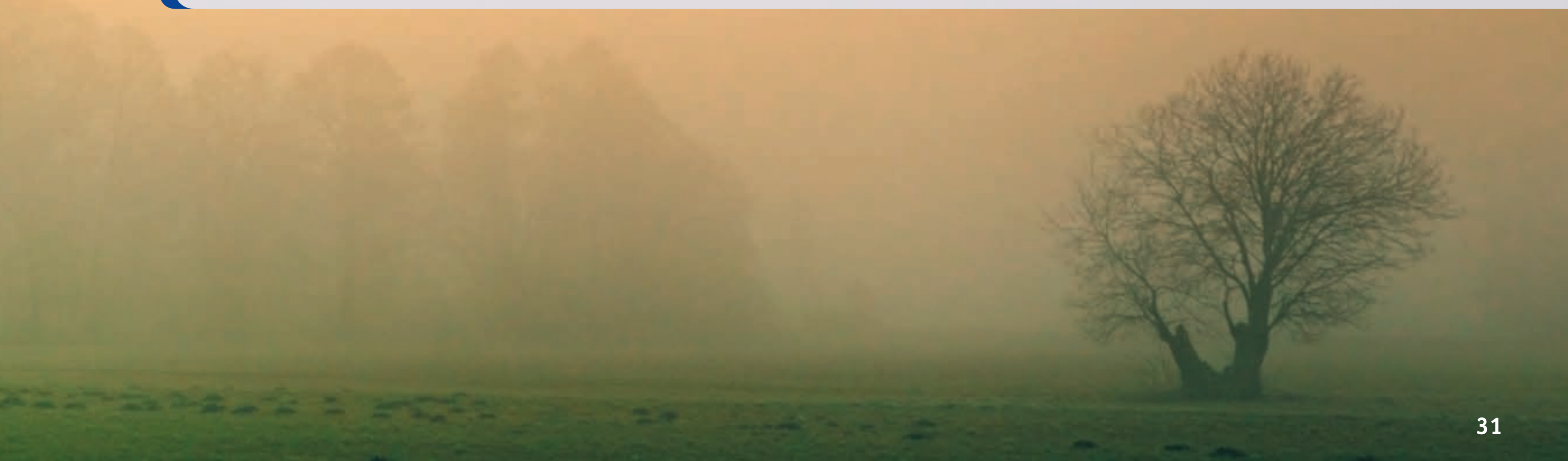
Energy: Warming and Cooling Earth and the Atmosphere

LEARNING OBJECTIVES

At the end of this section, you should be able to:

- **LO1** Define the terms energy, potential energy, kinetic energy, radiant energy, temperature, and heat.
- **LO2** Compare and contrast the Fahrenheit, Celsius, and Kelvin temperature scales.
- **LO3** Differentiate heat capacity, specific heat, latent heat, and sensible heat.
- **LO4** Describe the functions of conduction, convection, and advection in Earth's atmosphere.
- **LO5** Explain the relationship between radiation and temperature.
- **LO6** Apply the principles of radiant energy to the Sun and Earth, including the differences between longwave and shortwave radiation and visible, ultraviolet, and infrared radiation.
- **LO7** Explain the terms blackbody, radiative equilibrium temperature, selective absorber, and atmospheric window as they relate to the atmospheric greenhouse effect.
- **LO8** Discuss the enhancement of the atmospheric greenhouse effect from human activity, including recent and projected changes on climate and life on Earth.
- **LO9** Explain Earth's energy balance, including the processes that affect incoming energy from the sun and outgoing energy from Earth's surface and atmosphere.
- **LO10** Describe the solar wind and solar storms, including their effects on Earth's atmosphere.

AT HIGH LATITUDES AFTER DARKNESS HAS FALLEN a faint, white glow may appear in the sky. Lasting from a few minutes to a few hours, the light may move across the sky as a yellow green arc much wider than a rainbow; or, it may faintly decorate the sky with flickering draperies of blue, green, and purple light that constantly change in form and location, as if blown by a gentle breeze. For centuries curiosity and superstition have surrounded these eerie lights. An Inuit legend says they are lights from the lanterns of spirits welcoming new arrivals to the afterlife. Nordic sagas called them a reflection of fire that surrounds the seas of the north. Even today there are those who proclaim that the lights are reflected sunlight from polar ice fields. Actually, this light show in the Northern Hemisphere is the aurora borealis—the northern lights—which is caused by invisible particles bombarding our upper atmosphere. Anyone who witnesses this, one of nature's spectacular color displays, will never forget it.



Energy is everywhere. It is the basis for life. It comes in various forms: It can warm a house, melt ice, and drive the atmosphere, producing our everyday weather events. When the sun's energy interacts with our upper atmosphere, we see energy at work in yet another form, a shimmering display of light from the sky—the aurora. What, precisely, is this common, yet mysterious, quantity we call "energy"? What is its primary source? How does it warm Earth and provide the driving force for our atmosphere? And in what form does it reach our atmosphere to produce a dazzling display like the aurora?

To answer these questions, we must first begin with the concept of energy itself. Then we will examine energy in its various forms and learn how energy is transferred from one form to another in our atmosphere. Finally, we will look more closely at the sun's energy and its influence on our atmosphere.

2.1 Energy, Temperature, and Heat

LO1 LO2 LO3

By definition, **energy** is the ability or capacity to do work on some form of matter. (Matter is anything that has mass and occupies space.) Work is done on matter when matter is either pushed, pulled, or lifted over some distance. When we lift a brick, for example, we exert a force against the pull of gravity—we "do work" on the brick. The higher we lift the brick, the more work we do. So, by doing work on something, we give it "energy," which it can, in turn, use to do work on other things. The brick that we lifted, for instance, can now do work on your toe—by falling on it.

The total amount of energy stored in any object (internal energy) determines how much work that object is capable of doing. A lake behind a dam contains energy by virtue of its position. This is called *gravitational potential energy* or simply **potential energy** because it represents the potential to do work—a great deal of destructive work if the dam were to break, or positive work if it leads to hydroelectric power. The potential energy (PE) of any object is given as

$$PE = mgh$$

where m is the object's mass, g is the acceleration of gravity, and h is the object's height above the surface.

A volume of air aloft has more potential energy than the same volume of air just above the surface. This is because the air aloft has the potential to sink and warm through a greater depth of atmosphere. A substance also possesses potential energy if it can do work when a chemical change takes place. Thus, coal, natural gas, and food all contain chemical potential energy.

Any moving substance possesses energy of motion, or **kinetic energy**. The kinetic energy (KE) of an object is equal to half its mass multiplied by its velocity squared; thus

$$KE = \tfrac{1}{2}mv^2$$

Consequently, the faster something moves, the greater its kinetic energy; hence, a strong wind possesses more kinetic energy than a light breeze. Because kinetic energy also depends on the object's mass, a volume of water and an equal volume of air may be moving at the same speed, but, because the water has greater mass, it has more kinetic energy. The atoms and molecules that comprise all matter have kinetic energy due to their motion. This form of kinetic energy is often referred to as *heat energy*. Probably the most important form of energy in terms of weather and climate is the energy we receive from the sun—*radiant energy*.

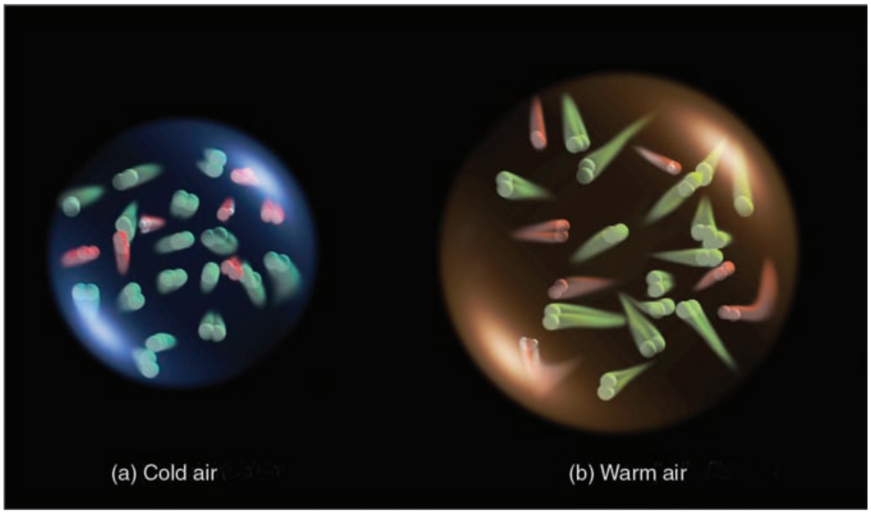
Energy, therefore, takes on many forms, and it can change from one form into another. But the total amount of energy in the universe remains constant. *Energy cannot be created, nor can it be destroyed*. It merely changes from one form to another in any ordinary physical or chemical process. In other words, the energy lost during one process must equal the energy gained during another. This is what we mean when we say that energy is conserved. This statement is known as the *law of conservation of energy*, and is also called the *first law of thermodynamics*.

We know that air is a mixture of countless billions of atoms and molecules. If they could be seen, they would appear to be moving about in all directions, freely darting, twisting, spinning, and colliding with one another like an angry swarm of bees. Close to Earth's surface, each individual molecule will travel only about a thousand times its diameter before colliding with another molecule. Moreover, we would see that all the atoms and molecules are not moving at the same speed, as some are moving faster than others. The temperature of the air (or any substance) is a measure of its average kinetic energy. Simply stated, **temperature** *is a measure of the average speed (average motion) of the atoms and molecules*, where higher temperatures correspond to faster average speeds.

Suppose we examine a volume of surface air about the size of a large flexible balloon, as shown in ● Fig. 2.1a. If we warm the air inside, the molecules will move faster, but they also will move slightly farther apart—the air becomes less dense, as illustrated in Fig. 2.1b. Conversely, if we cool the air back to its original temperature, the molecules would slow down, crowd closer together, and the air would become more dense. This molecular behavior is why, in many places throughout the book, we refer to surface air as either *warm, less-dense air* or as *cold, more-dense air*.

Along with temperature, we can also measure *internal energy*, which is the total energy (potential and kinetic) stored in a group of molecules. As we have just seen, the temperature of air and water is determined only by the *average* kinetic energy (average speed) of *all* their molecules. Because temperature only indicates how "hot" or "cold" something is relative to some set standard value, it does not always tell us the total amount of internal energy that something possesses. For example, two identical mugs, each half-filled with water and each with the same temperature, contain the same internal energy. If the water from one mug is poured into the other, the total internal energy of the filled mug has doubled because its mass has doubled. Its temperature, however, has not changed; the average speed of all of the molecules is still the same.

Now, imagine that you are sipping a hot cup of tea on a small raft in the middle of a lake. The tea has a much higher



● **FIGURE 2.1** Air temperature is a measure of the average speed (motion) of the molecules. In the cold volume of air, the molecules move more slowly and crowd closer together. In the warm volume, they move faster and farther apart.

temperature than the lake, yet the lake contains more internal energy because it is composed of many more molecules. If the cup of tea is allowed to float on top of the water, the tea would cool rapidly. The energy that would be transferred from the hot tea to the cool water (because of the temperature difference) is called *heat*.

In essence, **heat** *is energy in the process of being transferred from one object to another because of the temperature difference between the objects*. After heat is transferred, it is stored as internal energy. How is this energy transfer process accomplished? In the atmosphere, heat is transferred by *conduction*, *convection*, and *radiation*. We will examine these mechanisms of energy transfer after we look at temperature scales and at the important concepts of *specific heat* and *latent heat*.

2.1a TEMPERATURE SCALES

Suppose we take a small volume of air (such as the one shown in Fig. 2.1a) and allow it to cool. As the air slowly cools, its atoms and molecules would move more and more slowly until the air reaches a temperature of −273°C (−459°F), which is the lowest temperature possible. At this temperature, called **absolute zero**, the atoms and molecules would possess a minimum amount of energy and theoretically no thermal motion. Absolute zero is the starting point for a temperature scale called the *absolute scale*, or **Kelvin scale**, after Lord Kelvin (1824–1907), the British scientist who first introduced it. Because the Kelvin scale begins at absolute zero, it contains no negative numbers and is, therefore, quite convenient for scientific calculations.

The temperature scales most commonly used in meteorology are the Fahrenheit and Celsius (formerly centigrade) scales. The **Fahrenheit scale** was developed in the early eighteenth century by physicist G. Daniel Fahrenheit (1686–1736), who assigned the number 32 to the temperature at which water freezes, and the number 212 to the temperature at which water boils. The zero point was simply the lowest temperature that he obtained with a mixture of ice, water, and salt. Between the freezing and boiling points are 180 equal divisions, each of which is called a *degree*. A thermometer calibrated with this scale is referred to as a Fahrenheit thermometer, as it measures an object's temperature in degrees Fahrenheit (°F).

The **Celsius scale**, named after Swedish astronomer Anders Celsius (1701–1744), was introduced later in the eighteenth century and is part of the *metric system* used around the world. The number 0 (zero) on this scale is assigned to the temperature at which pure water freezes, and the number 100 to the temperature at which pure water boils at sea level. The space between freezing and boiling is divided into 100 equal degrees. Therefore, each Celsius degree is 180 / 100 or 1.8 times larger than a Fahrenheit degree. Put another way, an increase in temperature of 1°C equals an increase of 1.8°F. A formula for converting °F to °C is

$$°C = \tfrac{5}{9}(°F - 32)$$

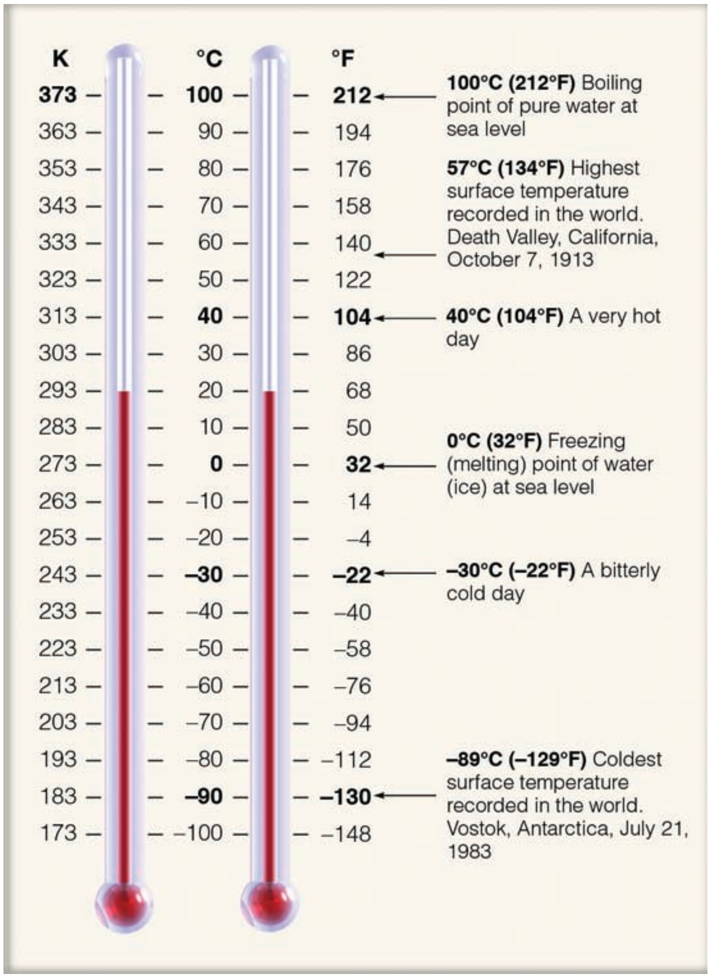
On the Kelvin scale, degrees kelvin are called *kelvins* (abbreviated K, without a degree sign). One Kelvin is exactly the same size as a degree Celsius, and a temperature of 0 K is equal to −273°C. Converting from °C to K can be done by simply adding 273 to the Celsius temperature, as

$$K = °C + 273$$

● Figure 2.2 compares the Kelvin, Celsius, and Fahrenheit scales. Converting a temperature from one scale to another can be done by simply reading the corresponding temperature from the adjacent scale. Thus, 303 K on the Kelvin scale is the equivalent of 30°C and 86°F*.

In nearly all of the world, temperature readings are taken in °C and public weather forecasts use the Celsius scale. In the United States and a few island nations and territories, however, temperatures above the surface are taken in °C while temperatures at the surface are typically read and reported in °F. Likewise, temperatures on upper-level maps are plotted in °C, while on surface weather maps they are in °F. Because both scales are in use in the United States, temperature readings in this book will, in most cases, be given in °C followed by their equivalent in °F.

*A more complete table of conversions is given in Appendix A.



● **FIGURE 2.2** Comparison of Kelvin, Celsius, and Fahrenheit scales, along with some world temperature extremes.

2.1b SPECIFIC HEAT

A watched pot never boils, or so it seems. The reason for water's slowness to boil is that water requires a relatively large amount of heat energy to bring about a small temperature change. The **heat capacity** of a substance is the ratio of the amount of heat energy absorbed by that substance to its corresponding temperature rise. The heat capacity of a substance per unit mass is called **specific heat**. In other words, specific heat is the amount of heat needed to raise the temperature of 1 gram (g) of a substance 1 degree Celsius.

If we heat 1 g of liquid water on a stove, it would take about 1 calorie (cal)* to raise its temperature by 1°C. So water has a specific heat of 1. If, however, we put the same amount (that is, same mass) of compact dry soil on the flame, we would see that it would take about one-fifth the heat (about 0.2 cal) to raise its temperature by 1°C. The specific heat of water is, therefore, five times greater than that of soil. In other words, water must absorb five times as much heat as the same quantity of soil in order to raise its temperature by the same amount. The specific heat of various substances is given in ▼ Table 2.1.

Not only does water heat slowly, it cools slowly as well. It has a much higher capacity for storing energy than other common substances, such as soil and air. A given volume of water can store a large amount of energy while undergoing only a small temperature change. Because of this attribute, water has a strong modifying effect on weather and climate. Near large bodies of water, for example, winters usually remain warmer and summers cooler than nearby inland regions—a fact well known to people who live adjacent to oceans or large lakes.

2.1c LATENT HEAT—THE HIDDEN WARMTH

We know from Chapter 1 that water vapor is an invisible gas that becomes visible when it changes into larger liquid or solid (ice) particles. This process of transformation is known as a *change of state* or, simply, a *phase change*. The heat energy required to change a substance, such as water, from one state to another is called **latent heat**. But why is this heat referred to as "latent"? To answer this question, we will begin with something familiar to most of us—the cooling produced by evaporating water.

Suppose we microscopically examine a small drop of pure water. At the drop's surface, molecules are constantly escaping (evaporating). Because the more energetic, faster-moving molecules escape most easily, the average motion of all the molecules left behind decreases as each additional molecule evaporates. Because temperature is a measure of average molecular motion, the slower motion suggests a lower water temperature. *Evaporation is, therefore, a cooling process*. The energy needed to evaporate the water—that is, to change its phase from a liquid to a gas—may come from the water or other sources, including the air.

In the everyday world, we experience evaporational cooling as we step out of a shower or swimming pool into a dry area. Because some of the energy used to evaporate the water comes from our skin, we may experience a rapid drop in skin temperature, even to the point where goose bumps form. In fact,

▼ **TABLE 2.1 Specific Heat of Various Substances**

SUBSTANCE	SPECIFIC HEAT Cal/(g × °C)	J/(kg × °C)
Water (pure)	1	4186
Wet mud	0.6	2512
Ice (0°C)	0.5	2093
Sandy clay	0.33	1381
Dry air (sea level)	0.24	1005
Quartz sand	0.19	795
Granite	0.19	794

*By definition, a calorie is the amount of heat required to raise the temperature of 1 g of water from 14.5°C to 15.5°C. The kilocalorie is 1000 calories and is the heat required to raise 1 kilogram (kg) of water 1°C. In the International System (Système International [SI]), the unit of energy is the joule (J), where 1 calorie = 4.186 J. (For pronunciation: *joule* rhymes with *pool*.)