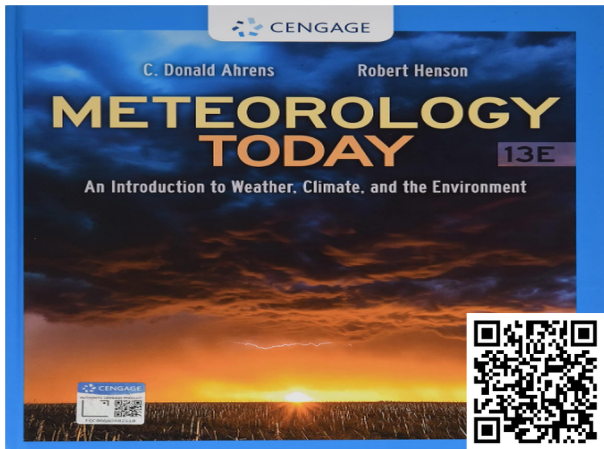


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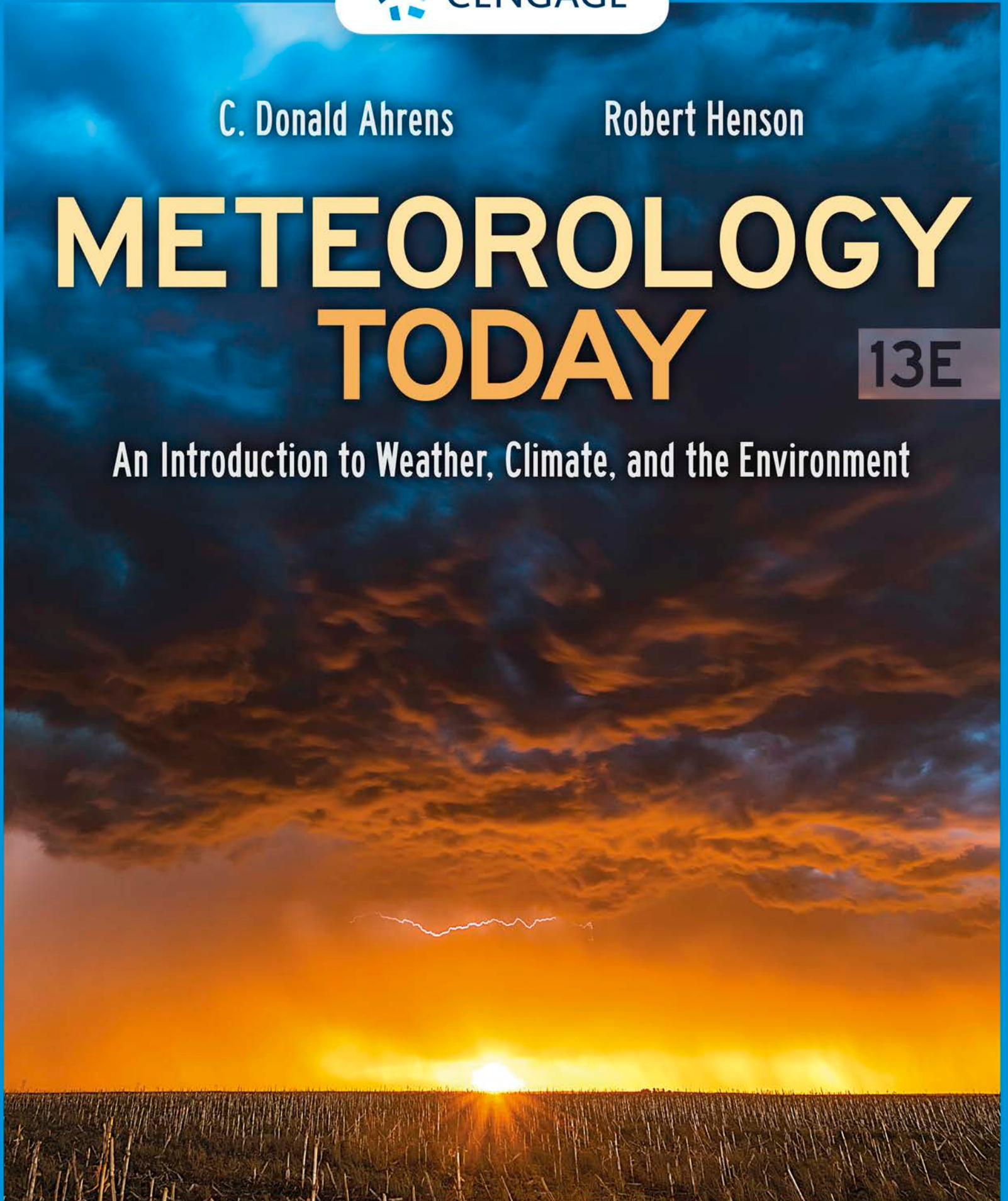
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AN INTRODUCTION TO WEATHER,
CLIMATE, AND THE ENVIRONMENT

C. Donald Ahrens

Emeritus, Modesto Junior College

Robert Henson



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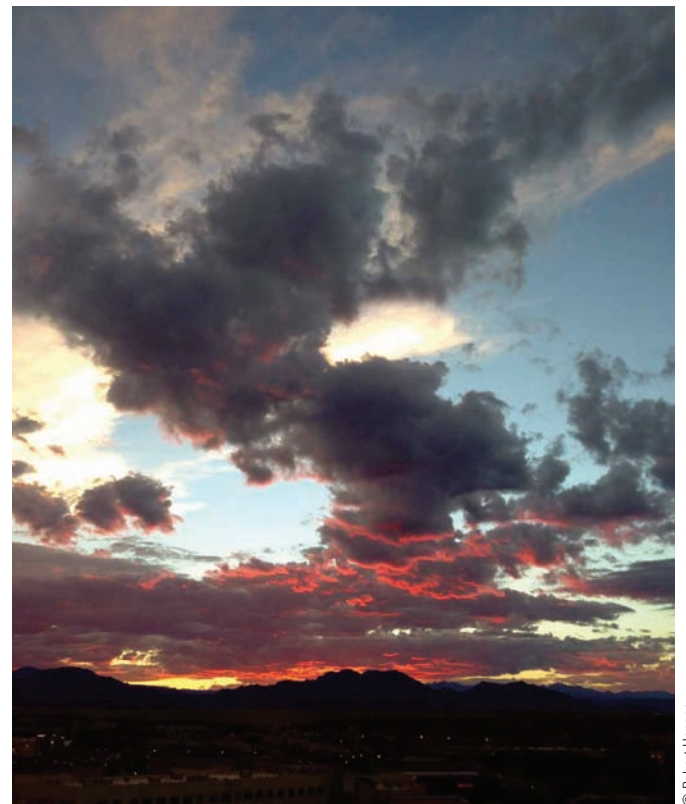
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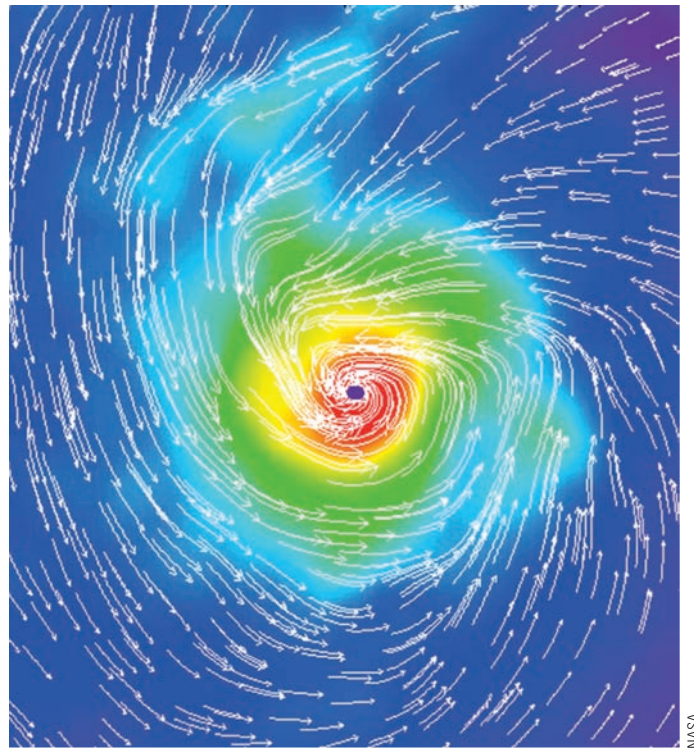


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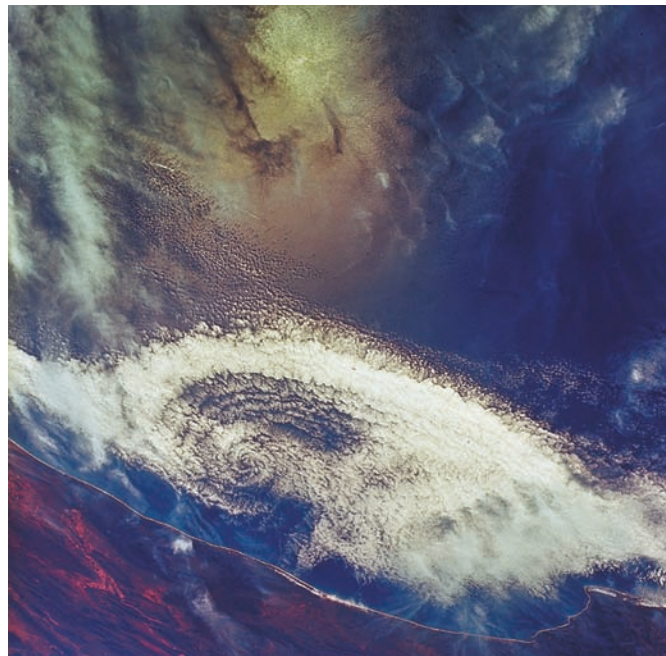
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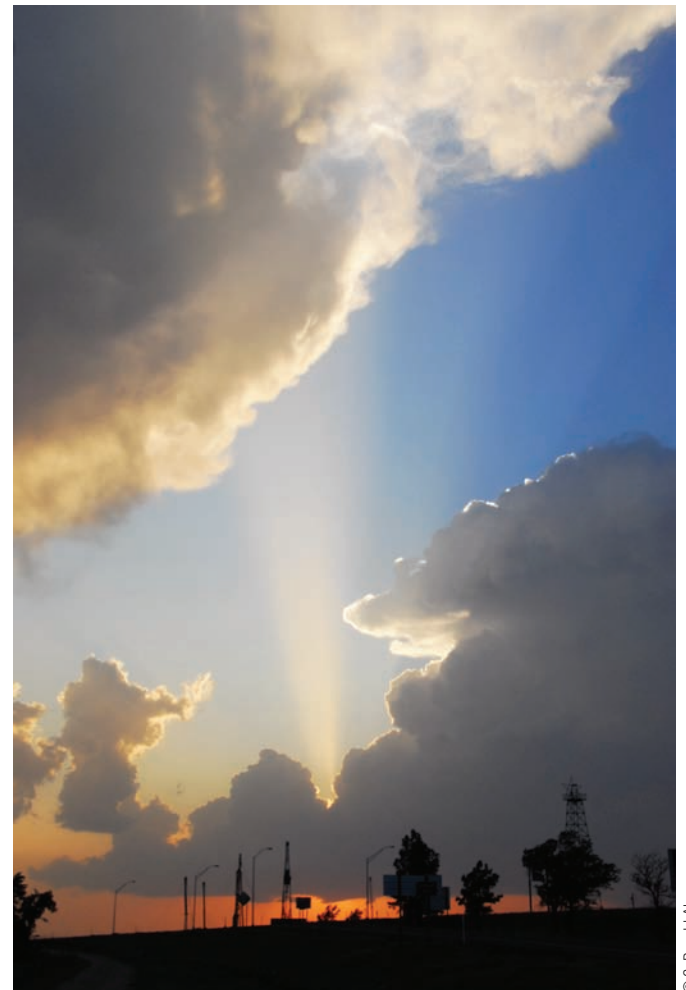
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Preface

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

Weather has always been front-page news, but in recent years, extreme weather 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
- Create multiple test versions in an instant
- Deliver tests from your LMS, your classroom, or wherever you want

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 anticyclonic 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

Earth and Its Atmosphere

LEARNING OBJECTIVES

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

- L01** List three ways the scientific method can be applied to studying the atmosphere and weather.
- L02** Outline the sequence of changes in nitrogen, oxygen, and water vapor over Earth's history.
- L03** Explain the role of gases (including water vapor, carbon dioxide, oxygen, and other greenhouse gases) and pollutants in Earth's atmosphere.
- L04** Describe how air density and air pressure are determined and how they vary as you move upward through Earth's atmosphere.
- L05** Describe the layers of the atmosphere, including their altitudes, temperatures, compositions, and functions.
- L06** Differentiate between weather and climate.
- L07** Interpret a weather map, applying storm types and concepts such as low pressure, high pressure, and front.
- L08** List the positive and negative effects of climate and weather on human health, agriculture, infrastructure, and the economy.

I WILL 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 Loeb sack, *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.

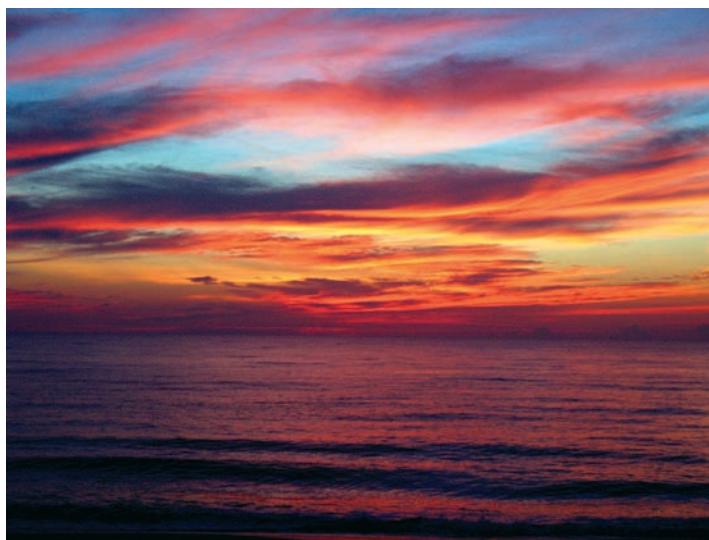
1.1 The Atmosphere and the Scientific Method

L01

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

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



UCAR, Photo by Carlie 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.”

grains of truth in some of them. However, they are not considered to be products of the scientific method because they are not tested and verified in a standard, rigorous way. (See ● Fig. 1.1.)

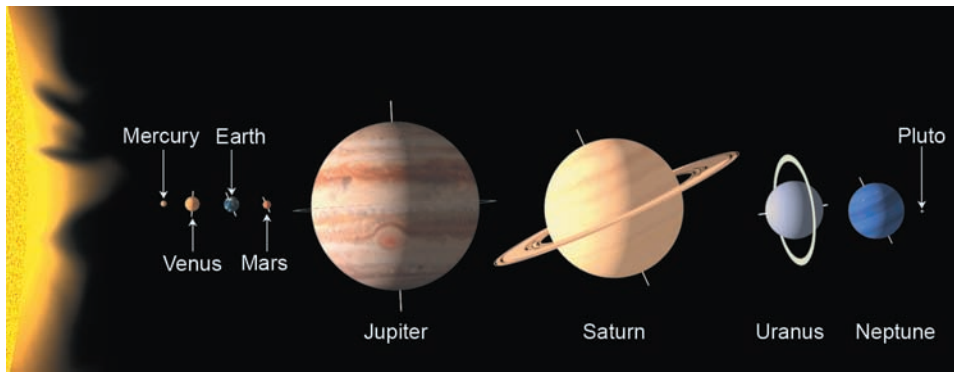
To be accepted, a hypothesis has to be shown to be correct through a series of quantitative tests. In many areas of science, such testing is carried out in a laboratory, where it can be replicated again and again. Studying the atmosphere, however, is somewhat different, because Earth has only one atmosphere.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

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

L02 L03

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



● **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* (CO₂). 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 (CH₄) and ammonia (NH₃). 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 (CO₂) were dissolved in the oceans. Through chemical and biological processes, much of the CO₂ became locked up in carbonate sedimentary rocks, such as limestone. With much of the water vapor already condensed and the concentration of CO₂ dwindling, the atmosphere gradually became dominated by molecular nitrogen (N₂), which is usually not chemically active.

It appears that molecular oxygen (O₂), 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 (H₂O) 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** (N₂) occupies about 78 percent and molecular **oxygen** (O₂) 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 (CO₂). The addition of oxygen to the atmosphere occurs during photosynthesis.

The concentration of the invisible gas **water vapor** (H₂O), 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 ₂ O	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 ₂ O	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

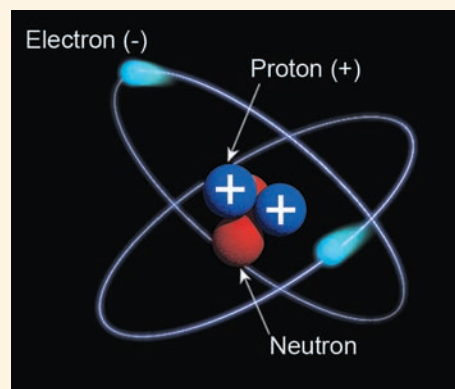
it changes from vapor into liquid water or ice. Latent heat is an important source of atmospheric energy, especially for storms, such as thunderstorms and hurricanes. Moreover, water vapor is a potent *greenhouse gas* because it strongly absorbs a portion of Earth's outgoing radiant energy (somewhat 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.

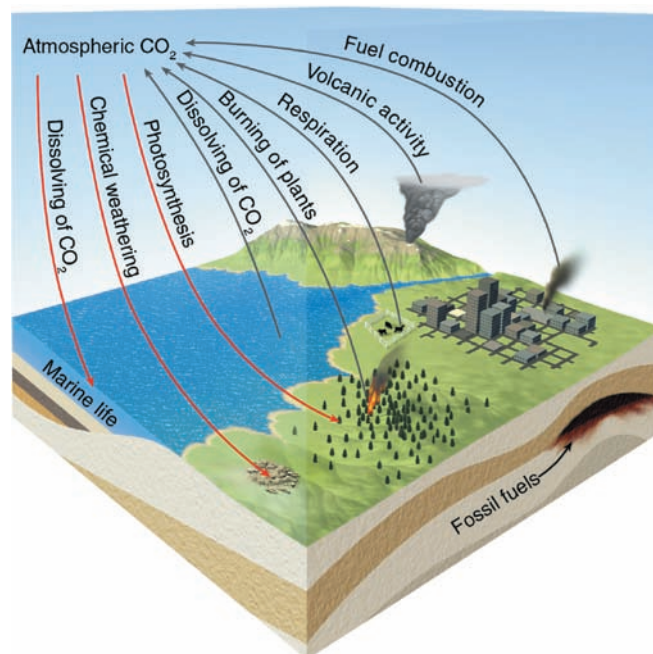
Each time we breathe, the molecules we exhale enter the turbulent atmosphere. If we wait a long time, those molecules will eventually become thoroughly mixed with all of the other air molecules. If none of the molecules were consumed in other processes, eventually there would be a molecule from that 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.



● **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.

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.

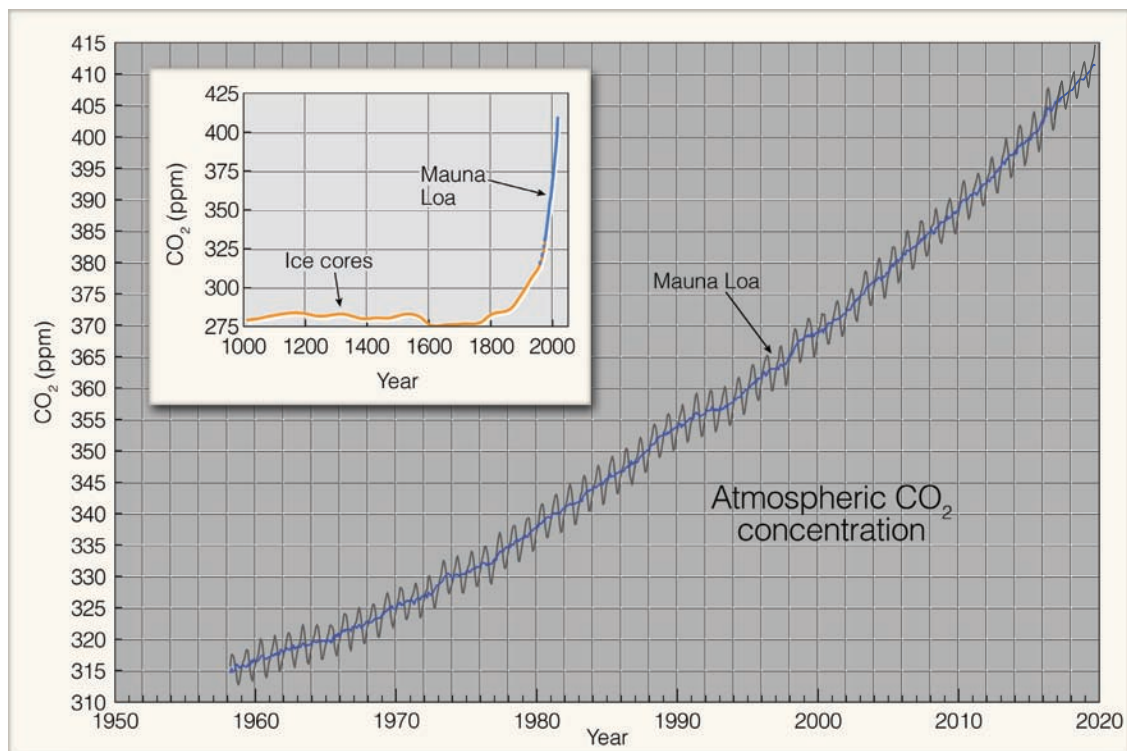
● Figure 1.6 reveals that the atmospheric concentration of CO_2 has risen by around 30 percent since 1958, when regular measurements began at Mauna Loa Observatory in Hawaii. This increase means that CO_2 is entering the atmosphere at a greater rate than it is being removed. The increase is caused mainly 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



● **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.

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 CO₂ 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 CO₂ to the atmosphere, and how lower readings occur in summer when more abundant vegetation absorbs CO₂ from the atmosphere. (b) The inset shows CO₂ 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* (CH₄), *nitrous oxide* (N₂O), 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** (O₃) 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*.

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