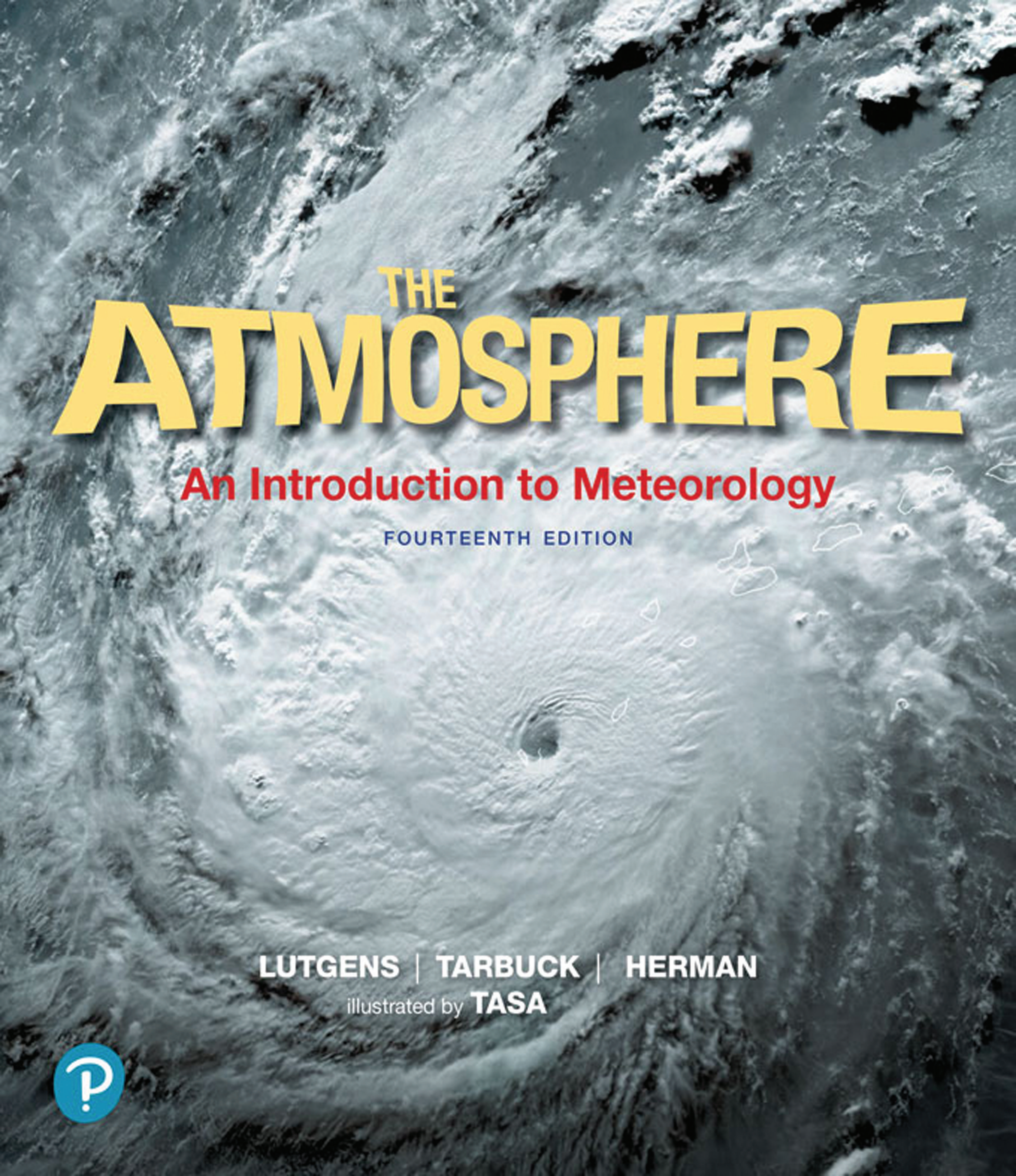

THE ATMOSPHERE

An Introduction to Meteorology

FOURTEENTH EDITION

LUTGENS | TARBUCK | HERMAN

illustrated by TASA

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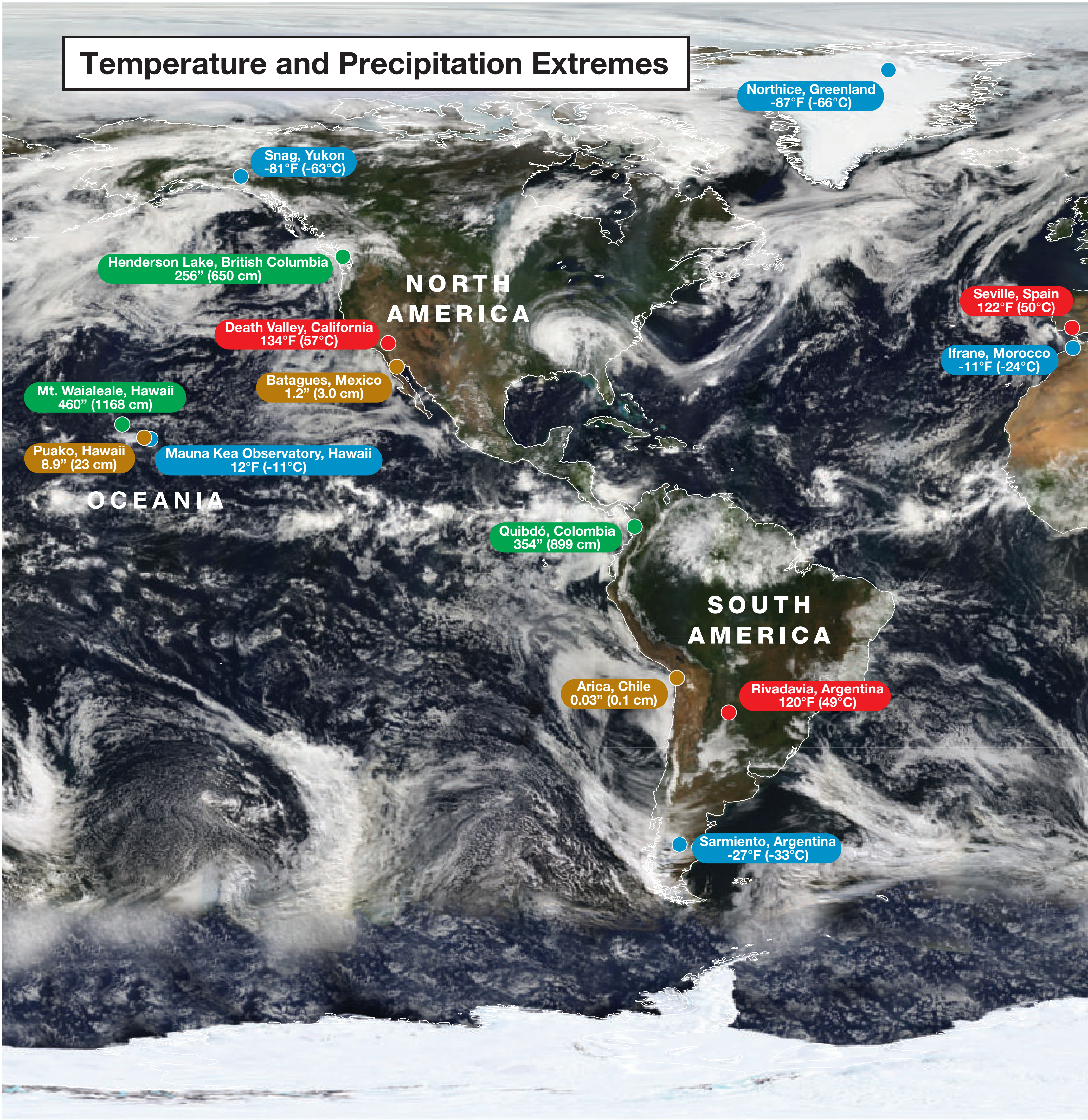
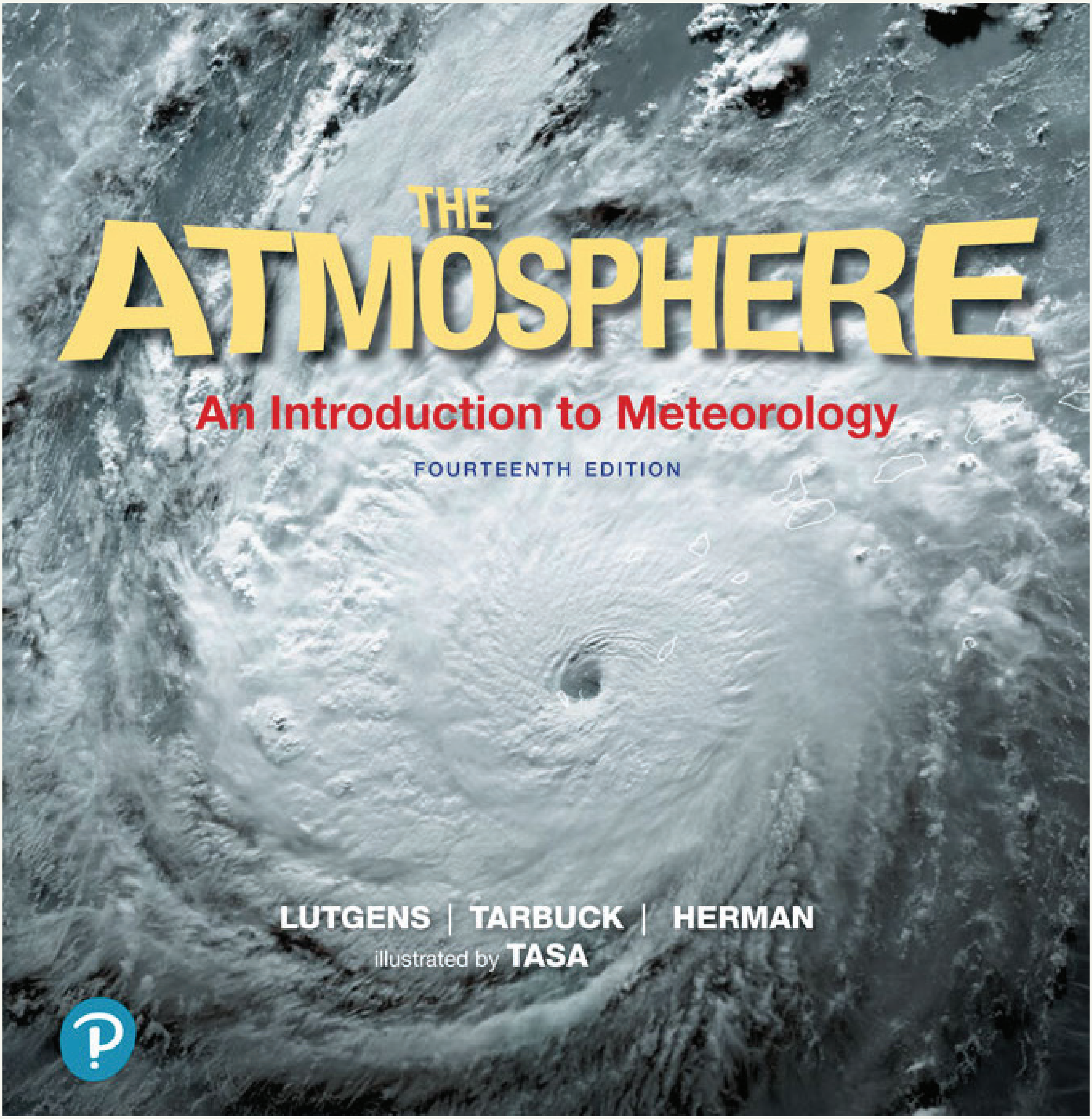


This photo-like view is based largely on observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASAs *Terra* satellite.


EUROPE
ASIA
AFRICA
OCEANIA
AUSTRALIA
ANTARCTICA
Verkhoyansk, Russia
-90° (-68°C)
Ust'-Shchuger, Russia
-67°F (-55°C)
Oymyakon, Russia
-90°F (-68°C)
Astrakhan', Russia
6.4" (16.3 cm)
Crkvica, Bosnia & Herzegovina
183" (465 cm)
Tirat Tsvi, Israel
129°F (54°C)
Kebili, Tunisia
131°F (55°C)
Mawsynram, India
467" (1187 cm)
Wadi Halfa, Sudan
<0.1" (<.03 cm)
Aden, Yemen
1.8" (4.6 cm)
Tuguegarao, Philippines
108°F (42°C)
Debundscha, Cameroon
405" (1029 cm)
Bellenden Ker, Queensland
340" (864 cm)
Cloncurry, Queensland
128°F (53°C)
Mulka, South Australia
4.05" (10.3 cm)
Charlotte Pass, New South Wales
-9°F (-23°C)
Extremes
by Continent
Highest temperature
Lowest temperature
Highest precipitation
Lowest precipitation
Vanda Station
59°F (15°C)
Vostok Station
-129°F (-89°C)
Amundsen-Scott South Pole Station
0.8" (2.0 cm)

The Perfect Storm of Rich Media and Active Learning Tools



Streamlined Learning Path Enables students to

Focus on CONCEPTS

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- **Explain what causes the Sun angle and length of daylight to change throughout the year. Describe how these changes result in seasonal changes in temperature (2.1).**
- **Describe the different forms of energy and heat in the atmosphere: kinetic energy, potential energy, latent heat, and sensible heat (2.2).**
- **List and describe the three mechanisms of heat transfer (2.3).**
- **Describe what happens to incoming solar radiation (2.4).**
- **Explain how the greenhouse effect works and why it is important (2.5).**
- **Describe the major components of Earth's annual energy budget (2.6).**

NEW! Active Learning Path An improved learning path now clarifies connections, highlights major concepts and reinforces key ideas as students move through the chapter—leading to greater mastery.

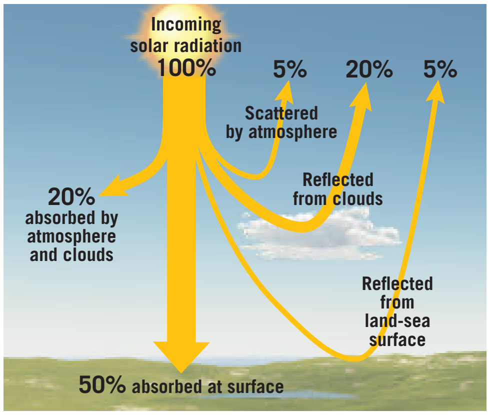
CONCEPTS IN REVIEW

2.4 What Happens to Incoming Solar Radiation?

- **Describe what happens to incoming solar radiation.**

Key Terms:	absorptivity	scattering	diffused light
transmission	reflection	albedo	

- Approximately 50 percent of the solar radiation that strikes the atmosphere reaches Earth's surface. About 30 percent is reflected back to space. Clouds and the atmosphere's gases absorb the remaining 20 percent of the incoming solar energy.



CONCEPT CHECKS 2.1

- Briefly explain the primary causes of the seasons.
- What is the significance of the Tropic of Cancer and the Tropic of Capricorn?
- After examining Table 2.1, write a general statement that relates the season, latitude, and the length of daylight.

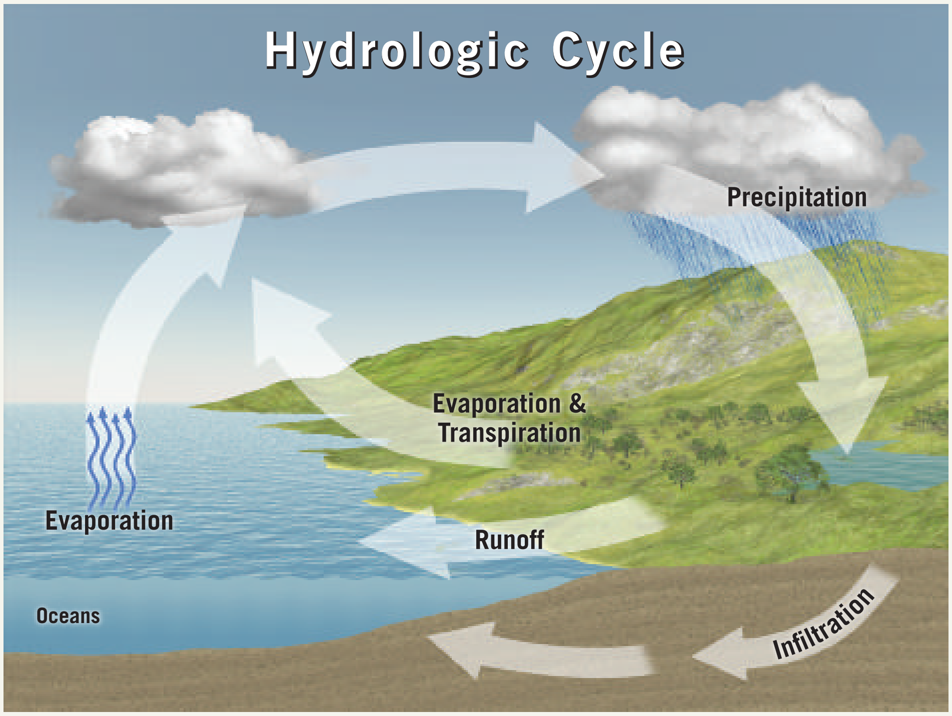
NEW! Key concepts highlighted in every section, serve as guideposts along the learning path helping students synthesize the section information.

front produces roughly the same amount of lifting as a warm front, but over a shorter distance, the precipitation is generally more intense but of shorter duration. A marked temperature drop and wind shift from the southwest to the northwest usually accompanies the passage of a cold front.

Prior to the arrival of a cold front, an area experiences an increase in winds from a southerly direction and warm temperatures, while a line of thunderstorms may be visible in the distance.

The weather following the passage of a cold front is dominated by subsiding air within a continental polar (cP) air mass.

Comprehend and Apply Key Concepts



▲ **SMARTFIGURE 4.1 Earth's hydrologic cycle**

Video
Hydrologic Cycle

UPDATED! Figures make learning easier by illustrating processes and examples in each chapter. Once again we are privileged to work with Dennis Tasa, whose artistic creations are stunning. There are **129 updated figures** that are new or substantially revised to help clarify difficult concepts. There are **49 updated photographs** of real-world weather situations to keep the textbook current and relevant.

NEW! Beyond the Textbook features 1-2 links to websites with atmospheric, weather, or climate data (animated maps, tables, diagrams, etc.) Students are asked questions based on current conditions or a specific locale. This allows students to see how concepts in the chapter play out in real life and in real time.

Beyond the Textbook

1. Water Vapor Satellite Loop

Water vapor provides the primary fuel for the stormy weather we experience. Watch the water vapor loop from GOES EAST at: http://www.ssec.wisc.edu/data/geo/. Click the button next to "Water Vapor

WEATHER SAFETY Southern California isn't the only place where wind can create dangerous fire hazards. These conditions can occur in any part of the United States. The National Weather Service issues a *Red Flag Warning* when strong winds, low relative humidity, and dry vegetation combine to create conditions in which fires will ignite quickly and grow rapidly. The following safety advice is given for areas under a Red Flag Warning:

- If you see even a small fire, report it immediately.
- Don't light fires, including campfires and barbeque grills.
- Don't park your car on or drive over dry grass.

NEW! Weather Safety Tips
Weather safety is fully integrated into the textbook. Every Severe & Hazardous Weather feature now contains **Weather Safety tips**. Weather safety tips are also added to the text in several chapters.

Continuous Learning
Before, During and After Class

Mastering Meteorology: Mastering Meteorology delivers engaging, dynamic learning opportunities focusing on course objectives and responsive to each student's progress–that are proven to help students absorb meteorology course material and understand challenging meteorology processes and concepts.

Mobile Media and Reading Assignments Ensure Students Come to Class Prepared.

NEW! Interactive Pearson eText gives students access to the text, anytime, anywhere. Pearson eText features include:

- Full eReader functionality
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- Accessible (screen-reader ready).
- Configurable reading settings, including resizable type and night reading mode.
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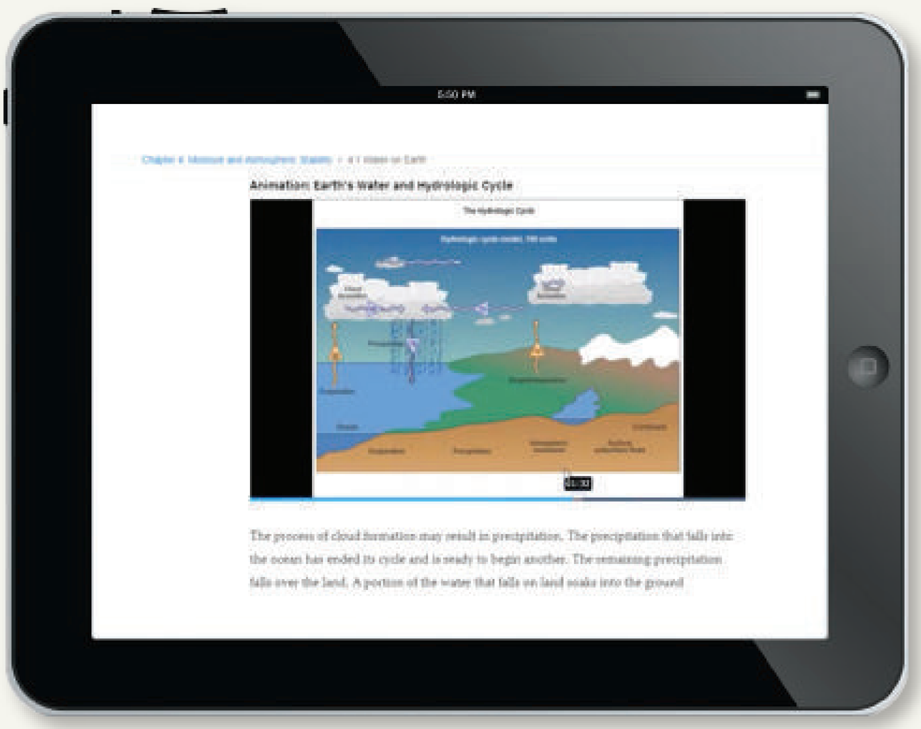
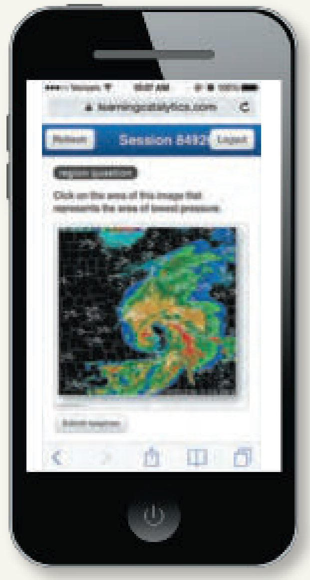


Pre-Lecture Reading Quizzes are easy to customize and assign

Reading Questions ensure that students complete the assigned reading before class. Reading Questions are 100% mobile ready and ca eted by students on mobile devices.

with Mastering Meteorology

Learning Catalytics, a “bring your own device” student engagement, assessment, and classroom intelligence system, allows students to use their smartphone, tablet, or laptop to respond to questions in class.



NEW & UPDATED!
Eye on the Atmosphere
which feature real-world imagery paired with active-learning questions, giving students a chance to practice visual analysis tasks as they read.

eye on the
ATMOSPHERE 3.1

Imagine being at this beach on a warm, sunny summer afternoon.

Apply What You Know

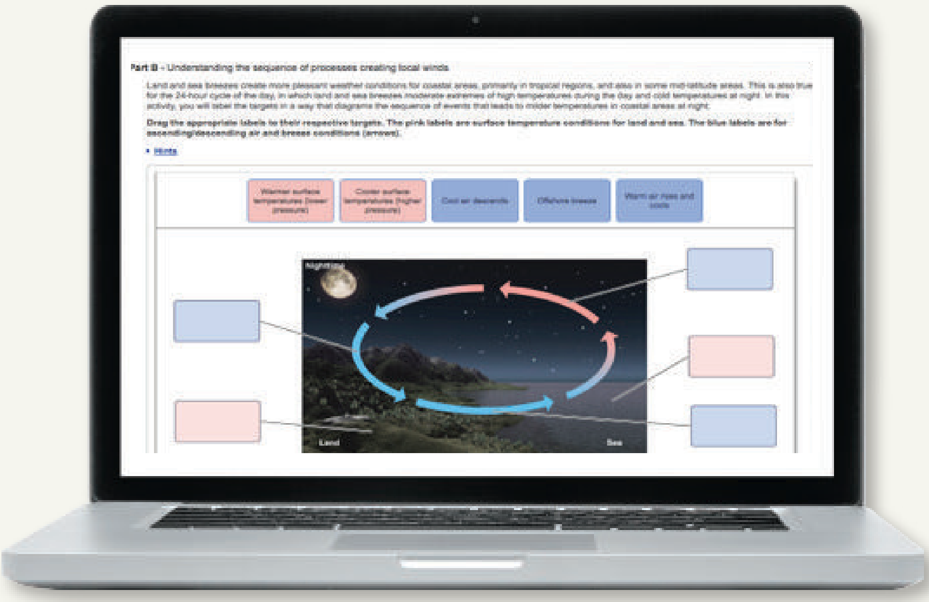
1. Describe the temperatures you would expect if you measured the beach surface and then at a depth of 12 inches.
2. If you stood waist deep in the water and measured the water’s surface temperature and the temperature at a depth of 12 inches, how would these measurements compare to those taken on the beach?

Continuous Learning

Easy to Assign, Customize, Media-Rich, and Atomically Graded Assignments.

NEW! MapMaster2.0 activities are inspired by GIS and allow students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. Now, **fully mobile,** activities include enhanced analysis tools, such as split screen, the ability for students to geolocate themselves in the data, and the ability for students to upload their own data. This tool includes zoom and annotation functionality, with hundreds of map layers leveraging recent data from sources such as NOAA, NASA, USGS, United Nations, CIA, World Bank, UN, PRB, and more.

with Mastering Meteorology

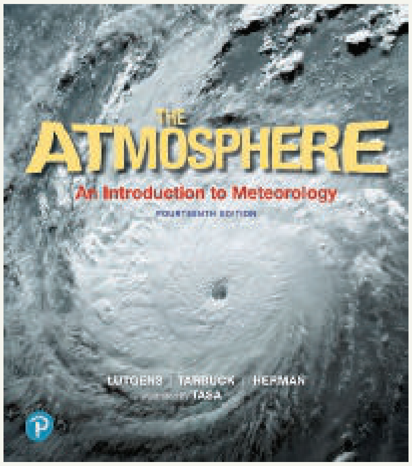


HALLMARK! GeoTutors. Highly visual coaching items with hints and specific wrong answer feedback help students master the toughest topics.

HALLMARK! Encounter Activities (GoogleEarth) activities provide rich, interactive explorations of human geography concepts, allowing students to visualize spatial data and tour distant place on the virtual globe.

HALLMARK! SmartFigures are brief, narrated video lessons that examine and explain concepts illustrated by key figures within the text. Students access SmartFigures on their mobile devices by scanning Quick Response (QR) codes next to key figures. These media are also available in the Study Area and can be assigned through Mastering Meteorology.

Resources for YOU, the Instructor



Mastering Meteorology provides you with everything you need to prep for your course and deliver a dynamic lecture, in one convenient place. Resources include:

MEDIA ASSETS FOR EACH CHAPTER
- *GeoVideos*
- MapMaster2.0
- Google Earth
- GeoTutors
- PowerPoints

TEST BANK
- Test Bank in Microsoft, Word, PDF, and RTF formats
- Computerized Test Bank, which includes all the questions from the printed test bank in a format that allows you to easily and intuitively build exams and quizzes.

TEACHING RESOURCES
- Instructor Resource and Support Manual in Microsoft Word and PDF formats
- Teaching with Student Learning Outcomes
- Learning Catalytics: Getting Started
- Lecture and Image PowerPoints
- Images

STUDENT SUPPLEMENTS
- Study Area
- QR Codes throughout
- Animations
- Chapter Quizzes
- Videos
- Flash Cards
- RSS Feeds

Measuring Student Learning Outcomes?
All of the Mastering Meteorology assignable content is tagged to book content and to Bloom's Taxonomy. You also have the ability to add your own learning outcomes, helping you track student performance against your learning outcomes. You can view class performance against the specified learning outcomes and share those results quickly and easily by exporting to a spreadsheet.

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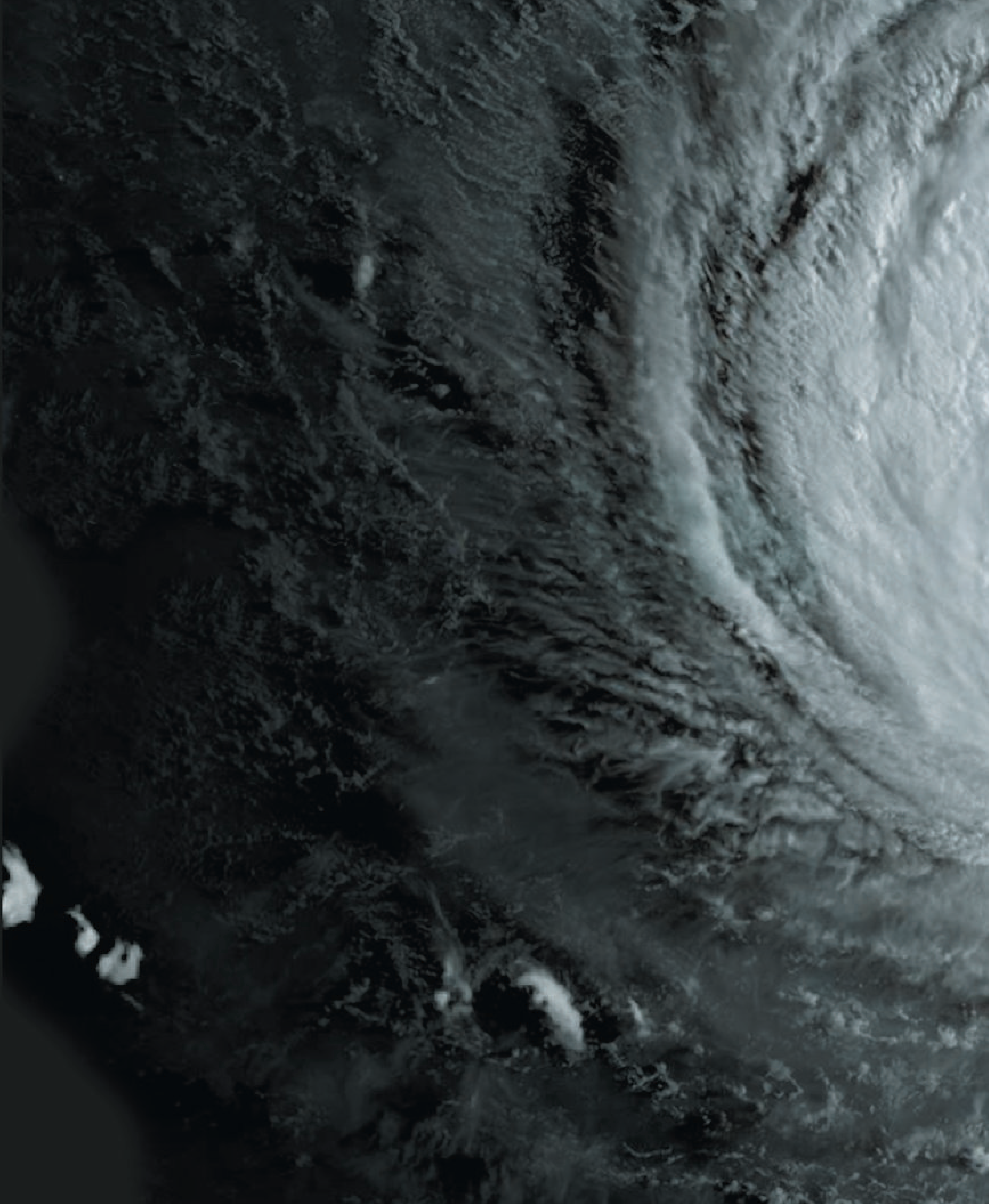
FOURTEENTH EDITION



THE ATMOSPHERE

An Introduction to Meteorology

FOURTEENTH EDITION

FREDERICK K. LUTGENS

EDWARD J. TARBUCK

REDINA L. HERMAN

illustrated by DENNIS TASA

Pearson

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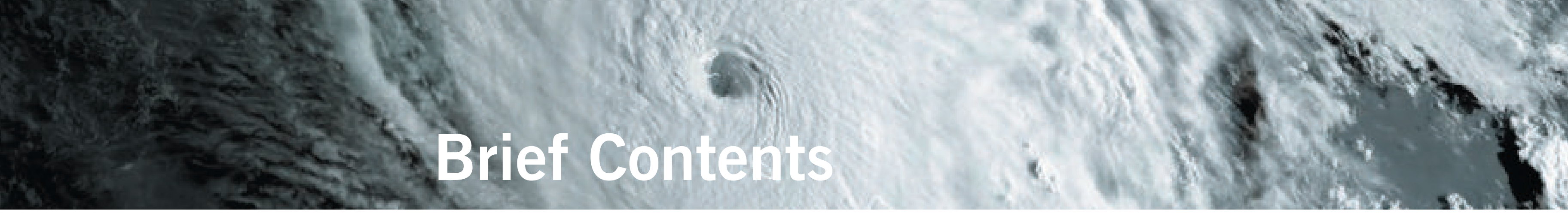

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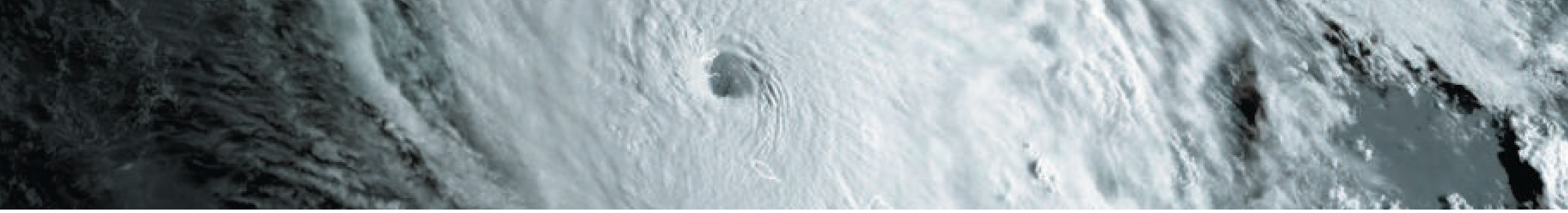

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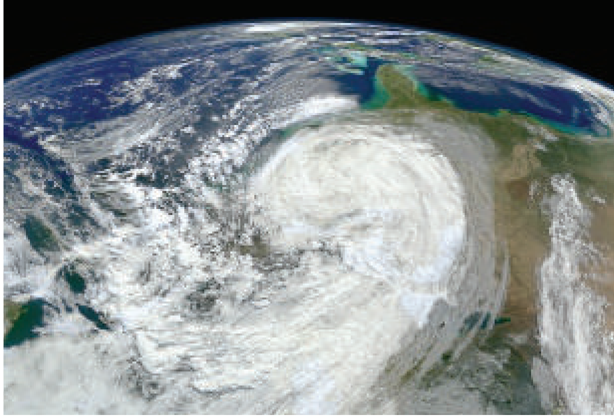







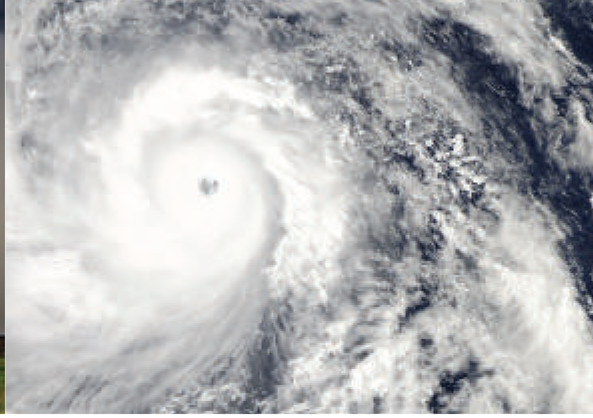







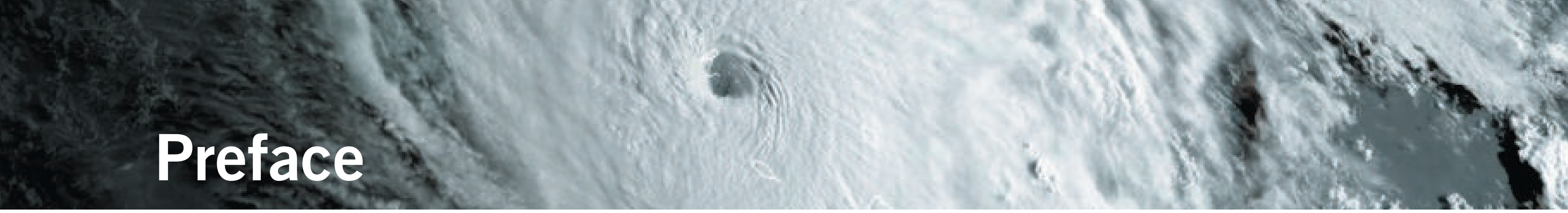

Preface

Weather is something we experience firsthand, but often we don't know why things happen the way they do. The fourteenth edition of *The Atmosphere* helps students understand why these things happen. This college-level textbook is a nontechnical survey of weather and the atmosphere, intended for students taking their first, and perhaps only, course in meteorology. Our goal in writing *The Atmosphere* is to help students understand the processes that control our weather and be able to apply this information in their daily lives.

New to This Edition

The fourteenth edition of *The Atmosphere* is streamlined to be more student oriented, with guideposts to a clear learning path from beginning to end of each chapter. We make use of experience gained from many years of teaching introductory weather and climate courses to add more process-oriented descriptions. Some chapters are reorganized and significantly revised to improve the flow of the discussion, and the material is updated based on current meteorology research. Most chapters have been reduced in length without cutting important content. Some of the textbook-wide changes include the following:

- An **improved active learning path** that creates a learning ladder, where each rung brings a deeper mastery of the material:
  - **Focus on Concepts**, appearing at the beginning of each chapter, lists learning objectives (many of which have been revised) to help students get a "lay of the land" before starting the chapter.
  - **Each major section** repeats the learning goal with a single bulleted visual to keep students focused.
  - Key concepts in every section are highlighted using one to two **pull quotes (NEW)** to help students synthesize the section information.
  - **Key terms** are in bold where they are defined in the text.
  - **Concept Checks** are a set of three to four questions placed at the end of each major section to help students test their recall of the main points of the section.
  - **Concepts in Review** tie back to Focus on Concepts (the learning objectives), summarize the main points (many revised) for each section, and now incorporate visual cues for each section to aid with recall and understanding. These reviews bring the learning path full circle for students.
  - **Review Questions (NEW)** provide students with an opportunity to test their understanding of the chapter as a whole.
  - Requiring a higher level of understanding, the **Give It Some Thought** section challenges students to synthesize concepts and apply this knowledge to answer questions.
  - **By the Numbers** (formerly called Problems) requires students to use basic math skills to solve quantitative problems related to key concepts.
  - **Beyond the Textbook (NEW)** features one to two links to websites with atmospheric, weather, or climate data (animated maps, tables, diagrams, etc.). Students answer data analysis questions based on actual current conditions or a specific locale. This allows students to see how concepts in the chapter play out in the real world and in real time.
- Updated figures make learning easier by illustrating processes and examples in each chapter. Once again we are privileged to work with Dennis Tasa, whose artistic creations are stunning. There are **129 figures** that are new or substantially revised to help clarify difficult concepts. There are **49 new photographs** of real-world weather situations to keep the textbook current and relevant.
- Weather safety is more fully integrated into the textbook. Every Severe & Hazardous Weather feature now contains **Weather Safety tips (NEW)**. Weather safety tips are also added to the text in several chapters.
- **Mastering Meteorology** delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help students absorb course material and understand difficult concepts.
  - **Integrated Mobile Media with accompanying review questions.** QR links to mobile-enabled *Videos* and *Geoscience Animations* are integrated throughout the chapters, giving students just-in-time access to animations of key physical processes and videos of real-world case studies and data visualizations. The video selection has been revised and updated. These media are also available in the Study Area of Mastering Meteorology. There are also short quizzes for each video in Mastering Meteorology.
  - **SmartFigures** are brief, narrated video lessons that examine and explain concepts illustrated by key figures within the text. Students access SmartFigures on their

- mobile devices by scanning Quick Response (QR) codes next to key figures. These media are also available in the Study Area of Mastering Meteorology, and teachers can assign them with automatically graded quizzes.
    - A **Math Review** chapter is added to Mastering Meteorology.
    - New end-of-chapter questions will be included in Mastering Meteorology.

- Significantly **updated and revised content**. A basic function of a college science textbook is to provide clear, understandable presentations that are accurate, engaging, and up-to-date. Our number-one goal is to keep *The Atmosphere* current, relevant, and highly readable for beginning students. In addition to new and improved figures, many discussions and examples have been updated and revised:

    - In Chapter 1, "Earth as a System" is revised with a new "What Powers the Earth System?" subsection. "Ozone Depletion: A Global Issue" is discussed in a new Box.
    - In Chapter 2, "Earth's Rotation and Orbit" is streamlined, and "The Greenhouse Effect" is revised.
    - "Daily Temperature Cycle" and "Annual Temperature Cycle" are presented earlier in Chapter 3, and "Why Temperatures Vary" is reorganized. The chapter's three boxes are updated.
    - In Chapter 4, the "Latent Heat" subsection is expanded, and "Atmospheric Stability" section is improved. A new box discusses the Stuve diagram.
    - In Chapter 5, "Precipitation Formation" provides more information on supercooled water, hail formation is expanded, and the radar discussion is updated.
    - In Chapter 6, "Measuring Atmospheric Pressure" includes electronic barometers. Pressure changes and friction discussions are revised to make these difficult concepts, and their relationship to wind, easier to understand. The chapter better explains the connections among curved flow aloft, convergence and divergence, rising and sinking motion, and surface wind systems.
    - Chapter 7 is significantly reorganized. "Scales of Atmospheric Motion" provides more examples, and "Land and Sea Breeze" is completely revised. "Global Distribution of Pressure and Precipitation" allows better comparison between the two, with discussion of monsoons incorporated into the pressure discussion. The "Jet Streams" section is revised, and the "El Niño, La Niña, and the Southern Oscillation" is expanded to include a direct comparison between normal and El Niño conditions, with a look at the 2015–2016 El Niño.
    - In Chapter 8, a new subsection, "Identifying Air Masses on Weather Maps," gives students practical skills, and a new box, "Heat Waves," is added. "Lake Effect Snow" discussion is moved to the "Air-Mass Modification" section.
    - The main sections in Chapter 9 are reorganized so that the cyclone models are discussed one after the other. Tables identifying the passage of fronts better match the discussion of frontal elements, and many figures are updated to complement the text.
    - Chapter 10 content is substantially improved and streamlined. The "Environment for Thunderstorm Development" subsection is revised, and "Ordinary Cell Thunderstorms" and "Severe Thunderstorms" sections are expanded. The radar discussion is updated under "Tornado Forecasting."
    - In Chapter 11, most main sections are renamed and reorganized. Hurricane components are discussed in more detail, and the section "Tracking and Monitoring Hurricanes" is updated and expanded to include aircraft reconnaissance.
    - Forecasting information already addressed in earlier chapters is condensed in Chapter 12 to focus on updates to "Modern Weather Forecasting," particularly weather satellites, quantitative forecasting, and thermodynamic diagrams.
    - Air pollution statistics in Chapter 13 are updated, and the discussion of atmospheric stability improved.
    - Chapter 14 incorporates the most recent IPCC findings. "Predicting Future Climate Change" is revised and updated.
    - Chapter 15 is streamlined to focus on controls of climate and the main differences between climate types.
    - In Chapter 16, the discussion of mirages is improved.

Distinguishing Features

Focus on Readability and Student Understanding

The language of this text is straightforward and *written to be understood*. Clear, readable discussions with a minimum of technical language are the rule. Frequent headings and subheadings help students follow discussions and identify the important ideas presented in each chapter. In the fourteenth edition, we have continued to improve readability by examining chapter organization and flow and by writing in a more personal style. Every chapter has been condensed to streamline the material and focus on key concepts. Significant portions of several chapters were rewritten and reorganized to improve the flow from one concept to the next.

This course is intended for general-education students taking their first meteorology course. It does not try to go into every detail about weather systems—there are more advanced courses for that. While this book is written at a general-education level, it can certainly be used as a launching point for students who want to pursue the study of meteorology.

Focus on Basic Principles

Although many topical issues are addressed in the fourteenth edition of *The Atmosphere*, it should be emphasized that the main focus of this new edition remains the same: to promote student understanding of basic principles. As much as possible, we have attempted to provide the reader with a sense of the observational techniques and reasoning processes that constitute the science of meteorology.

Additional Learning Aids

In addition to the new and expanded learning path, the fourteenth edition continues to include these important learning aids:

- **Eye on the Atmosphere** features real-world imagery paired with active-learning questions to give students a chance to practice visual analysis tasks as they read. Instructors can discuss these in class or assign the questions to students from the book or MasteringMeteorology.
- Every chapter includes several **You might have wondered . . .** (formerly Students Sometimes Ask) features. Instructors and students continue to react favorably and indicate that the questions and answers sprinkled through each chapter add interest and relevance to discussions.
- The new edition continues to highlight **severe and hazardous weather**. Atmospheric hazards adversely affect millions of people worldwide every day. Severe weather events have a significance and fascination that go beyond ordinary weather phenomena. In addition to the two chapters focused entirely on thunderstorms and tornadoes (Chapter 10) and hurricanes (Chapter 11), the text contains 15 Severe and Hazardous Weather boxes devoted to a broad variety of topics—heat waves, winter storms, floods, air pollution episodes, drought, wildfires, cold waves, and more. Each box now includes **Weather Safety tips** and one or two active-learning questions to help students test their understanding and link these events to critical chapter concepts.

Acknowledgments

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We would like to welcome Redina Herman to the team. Redina has a PhD in atmospheric science from the University of Illinois, Urbana–Champaign. She has been teaching introductory and advanced meteorology courses for 15 years. Redina is involved in science education research and won the Western Illinois University College of Arts and Sciences award for Outstanding Teaching with Technology. Redina is also Western Illinois University's representative to the University Corporation for Atmospheric Research (UCAR), which runs the National Center for Atmospheric Research (NCAR). She adds a great deal of knowledge, experience, and enthusiasm to the team.

Last, but certainly not least, we gratefully acknowledge the support and encouragement of our significant others, Nancy Lutgens, Joanne Bannon, and Owen Finch. Preparation of *The Atmosphere*, fourteenth edition, would have been far more difficult without their patience and understanding.

Fred Lutgens

Ed Tarbuck

Redina Herman

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For Students & Teachers

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- ***Geoscience Animation Library on DVD,*** **5th Edition [0321716841]** Created through a unique collaboration among Pearson's leading geoscience authors, this resource offers over 100 animations covering the most difficult-to-visualize topics in meteorology, Earth science, physical geography, physical geology, and oceanography. Animations include audio narration and text transcript, with assignable multiple-choice quizzes to select animations in Mastering Meteorology to help students master these core physical process concepts.
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For Students

- ***Exercises for Weather & Climate*****, 9th edition, by Greg Carbone [0134041364]** This bestselling exercise manual's 17 exercises encourage students to review important ideas and concepts through problem solving, simulations, and guided thinking. The graphics program and computer-based simulations and tutorials help students grasp key concepts. Now with mobile-enabled Pre-Lab Videos and Pre- and Post-Lab quizzes in Mastering Meteorology, this manual is designed to complement any introductory meteorology or weather and climate course.
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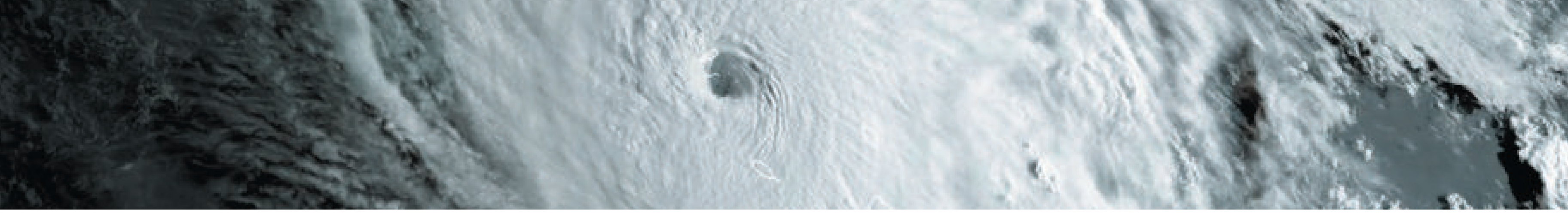

- ***Dire Predictions: Understanding Global Climate Change*, 2nd edition, by Mike Mann and Lee Kump [0133909778]** Periodic reports from the Intergovernmental Panel on Climate Change (IPCC) evaluate the risk of climate change brought on by humans. In just over 200 pages, this practical text presents and expands upon the essential findings of the IPCC in a visually stunning and undeniably powerful way to the lay reader. Scientific findings that provide validity to the implications of climate change are presented in clear-cut graphic elements, striking images, and understandable analogies. The second edition covers the latest climate change data and scientific consensus from the IPCC *Fifth Assessment Report* and integrates mobile media links to online media. The text is also available in various eText formats, including as a secondary eText upgrade option from *Elemental Geosystems' Mastering Geography*™ courses.
- ***Encounter Physical Geography* by Jess C. Porter and Stephen O'Connell [0321672526]** Pearson's Encounter Series provides rich, interactive explorations of geoscience concepts through Google Earth activities, covering a range of topics in meteorology and physical geography. For those who do not use Mastering Meteorology, all chapter explorations are available in print workbooks, as well as in online quizzes at www.mygeoscienceplace.com, accommodating different classroom needs. Each exploration consists of a worksheet, a corresponding Google Earth KMZ file, and online quizzes whose results can be e-mailed to teachers.

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  - "Clicker" questions in PowerPoint™, which correlate to the text's Learning Outcomes, U.S. National Geography Standards, and Bloom's taxonomy.
  - The TestGen software, *Test Bank* questions, and answers for both MACs and PCs.
  - Electronic files of the *Instructor Resource Manual* and *Test Bank*.

This Instructor Resource content is available online via the Instructor Resources section of Mastering Meteorology and www.pearsonhighered.com/irc.

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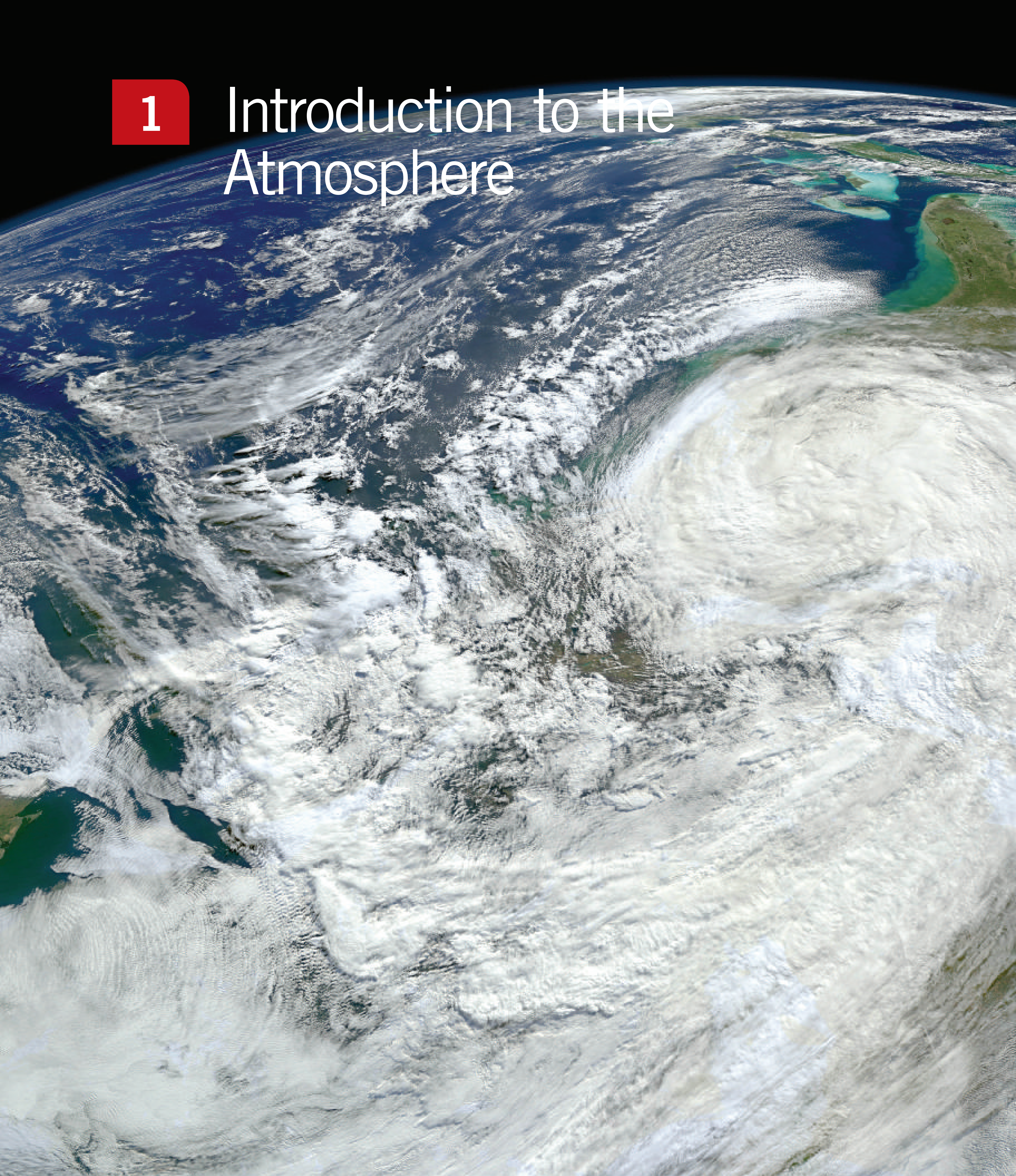
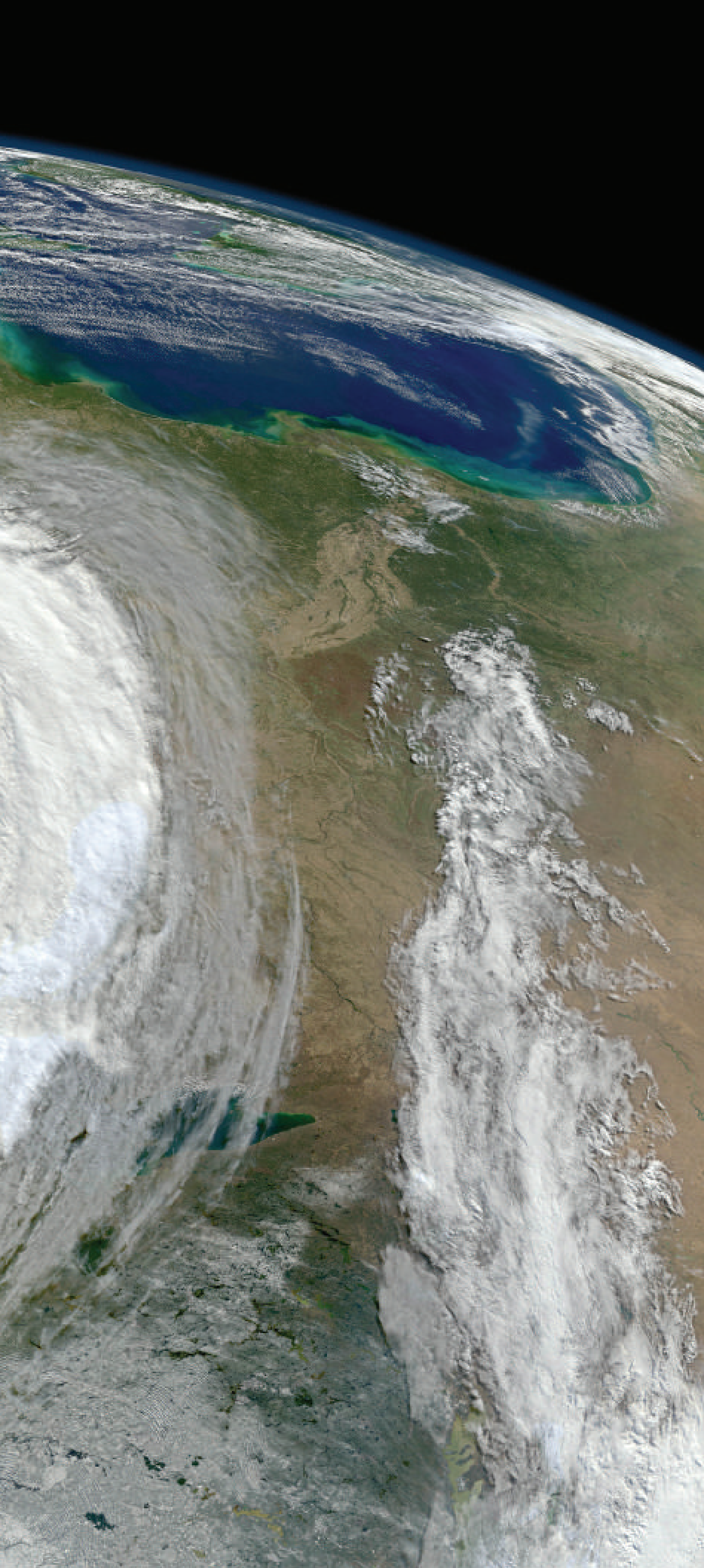
THE ATMOSPHERE

An Introduction to Meteorology

FOURTEENTH EDITION

1 Introduction to the Atmosphere





Focus on CONCEPTS

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- **Distinguish between weather and climate, name the basic elements of weather and climate, and list several important atmospheric hazards (1.1).**
- **Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories (1.2).**
- **List and describe Earth's four major spheres. Define *system*, and explain why Earth is considered a system (1.3).**
- **List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically (1.4).**
- **Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows the thermal structure of the atmosphere (1.5).**

Earth's atmosphere is unique. No other planet in our solar system has an atmosphere with the exact mixture of gases or the heat and moisture conditions necessary to sustain life as we know it. The gases that make up Earth's atmosphere and the controls to which they are subject are vital to our existence. In this chapter we begin our examination of the ocean of air in which we all must live.

This satellite image shows Hurricane Sandy, called Superstorm Sandy in the media, battering the U.S. east coast on October 30, 2012. This view of the storm is looking south from Canada. Florida is near the top of the image.

1.1 Focus on the Atmosphere

- **Distinguish between weather and climate, name the basic elements of weather and climate, and list several important atmospheric hazards.**

Weather influences our everyday activities, our jobs, and our health and comfort. Many of us pay attention to the weather only when it inconveniences us or when it adds to our enjoyment of outdoor activities. Nevertheless, few other aspects of our physical environment affect our lives more than the phenomena we collectively call the weather.

▲ **Figure 1.2 People influence the atmosphere** China is plagued by air quality issues. Major contributors of air pollutants in the region are coal-fired electricity generating plants.

Weather in the United States

The United States occupies an area that stretches from the tropics to the Arctic Circle. It has thousands of miles of coastline and extensive regions far from the influence of the ocean. Some landscapes are mountainous, and others are dominated by plains. Pacific storms strike the west coast, while the eastern states are sometimes influenced by events in the Atlantic and the Gulf of Mexico. The states in the center of the country commonly experience weather events triggered when frigid southward-bound Canadian air masses clash with northward-moving tropical air masses from the Gulf of Mexico.

The United States likely has the greatest variety of weather of any country in the world. Severe weather events such as tornadoes, flash floods, and intense thunderstorms, as well as hurricanes and blizzards, are collectively more frequent and more damaging in the United States than in any other nation (**Figure 1.1**). Beyond its direct impact on the lives of individuals, weather strongly affects the U.S. economy through its influence on agriculture, energy use, water resources, and transportation.

Weather influences our lives a great deal. Yet it is also important to realize that people influence the atmosphere and its behavior as well. There are, and will continue to be, significant economic, political, and scientific decisions to make involving these human impacts. Dealing with the effects of and controlling air pollution is one example (**Figure 1.2**). Another is the ongoing effort to assess and address global climate change. There is clearly a need for increased awareness and understanding of our atmosphere and its behavior.

▼ **Figure 1.1 An extraordinary winter** The winter of 2013–2014 brought record-breaking cold and snow to much of the eastern half of the conterminous United States. Meanwhile, Alaska and much of the West were much warmer and drier than usual.

Meteorology, Weather, and Climate

The subtitle of this book includes the word *meteorology*. **Meteorology** is the scientific study of the atmosphere and the phenomena that we usually refer to as *weather*. Acted on by the combined effects of Earth's motions and energy from the Sun, our planet's formless and invisible envelope of air reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. Although not identical, weather and climate have much in common.

Weather refers to the state of the atmosphere at a given time and place. Weather is constantly changing, sometimes from hour to hour and at other times from day to day. Whereas changes in the weather are continuous and sometimes seemingly erratic, it is nevertheless possible to arrive at a generalization of these variations. Such a description of aggregate weather conditions is termed **climate**. It is based on observations that have been accumulated over many decades. *Climate* is often defined simply as "average weather," but this definition is inadequate. An accurate portrayal of an area's climate must also include variations and extremes, as well as the probabilities that such departures from the norm will take place. For example, farmers need to know the average temperature during their area's growing season, but they must also know the date in the spring when the last freezing temperatures are most likely to occur.

Weather refers to the state of the atmosphere at a given time and place.

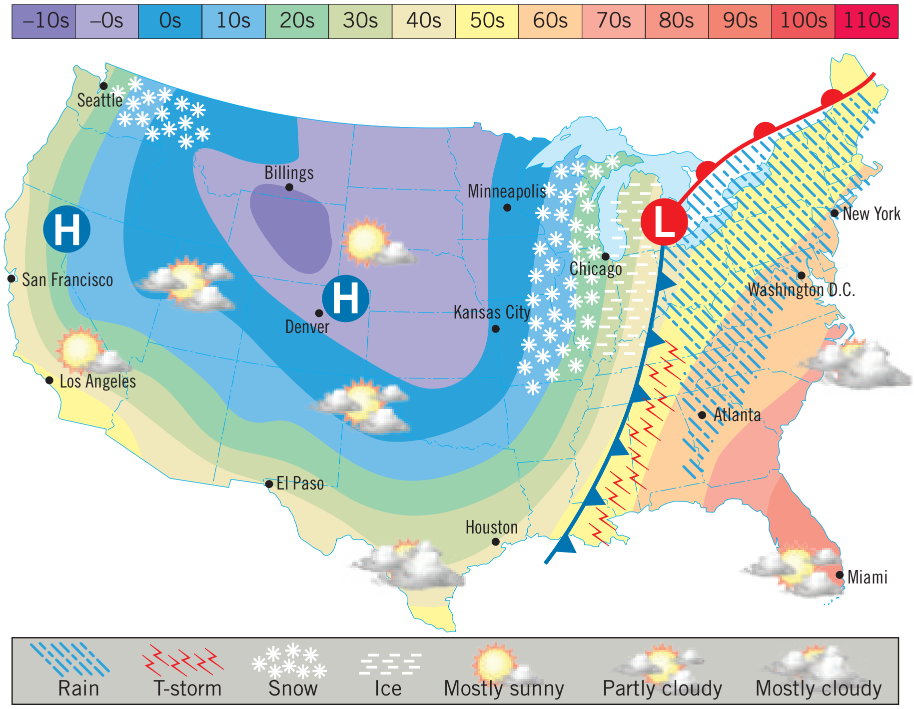
Maps like the one in **Figure 1.3** are familiar to everyone who checks the weather report from a website, a newspaper, or on television. In addition to showing predicted high temperatures for the day, this type of map shows other basic weather information about cloud cover, precipitation, and the location of fronts.

Suppose you were planning a vacation trip to an unfamiliar place. You would probably want to know what kind of weather to expect. Such information would help you select which clothes to pack and could influence what you decide to do during your stay. Unfortunately, weather forecasts that go beyond a few days are not very dependable. Thus, it may not be possible to get a reliable weather report about the conditions you are likely to encounter during your vacation.

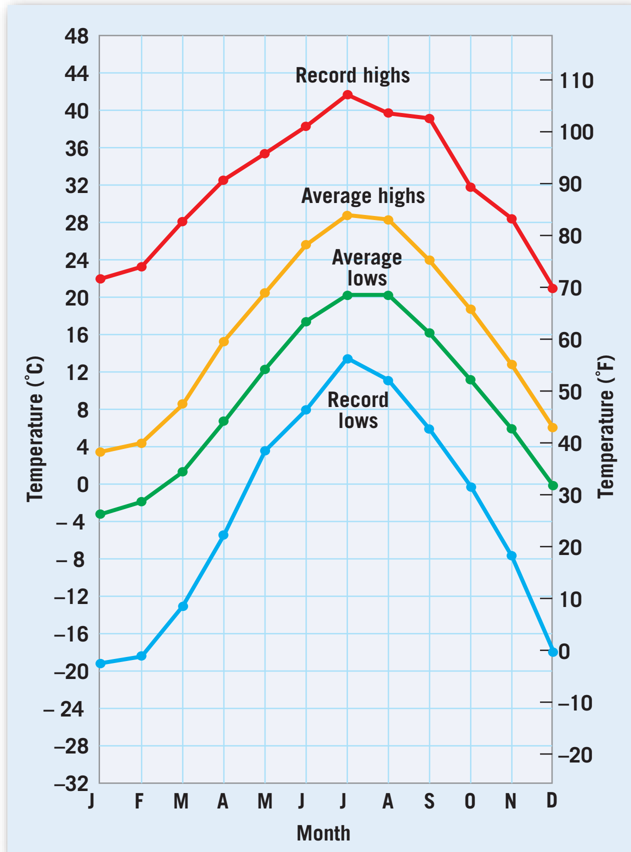
Instead, you might ask someone who is familiar with the area about what kind of weather to expect. "Are thunderstorms common?" "Does it get cold at night?" "Are the afternoons sunny?" What you are seeking is information about the climate, the conditions that are typical for that place. Another useful source of such information is the great variety of climate tables, maps, and graphs that are available. For example, the graph in **Figure 1.4** shows average daily high and low temperatures for each month, as well as extremes, for New York City.

Climate is the average of all weather data, including extremes, that helps to describe the environment of a place or region.

Such information could, no doubt, help as you planned your trip. But it is important to realize that *climate data cannot predict the weather*. Although the place may usually (climatically) be warm, sunny, and dry during the time of your planned vacation, you may in fact experience cool, overcast, and rainy weather. A well-known saying summarizes the distinction



▲ **Figure 1.3 Typical weather map for a day in late December** The colored bands show predicted high temperatures for the day.



▲ **Figure 1.4 New York City temperatures** In addition to the average maximum and minimum temperatures for each month, extremes are also shown. The graph is based on data collected during a 30-year span and shows that significant departures from the average can occur.

You might have wondered . . .

Does meteorology have anything to do with meteors?

There is a connection. The term *meteorology* was coined in 340 BCE, when the Greek philosopher Aristotle wrote a book titled *Meteorlogica*, which described atmospheric and astronomical phenomena. In Aristotle's day, *anything* that fell from or was seen in the sky was called a meteor. Today, however, we distinguish particles of ice or water in the atmosphere from extraterrestrial objects—meteoroids, or meteors.

between weather and climate: "Climate is what you expect, but weather is what you get."

The nature of both weather and climate is expressed in terms of the same basic properties, or *elements*, that are measured regularly. The most important are (1) the *temperature* of the air, (2) the *humidity* of the air, (3) the type and amount of *cloudiness*, (4) the type and amount of *precipitation*, (5) the *pressure* exerted by the air, and (6) the speed and direction of the *wind*. These elements constitute the variables by which weather patterns and climate types are depicted, and many of these are shown as map symbols in Figure 1.3. Although you will study these elements separately at first, keep in mind that they are very much interrelated. A change in one of the elements often produces changes in the others.

Atmospheric Hazards

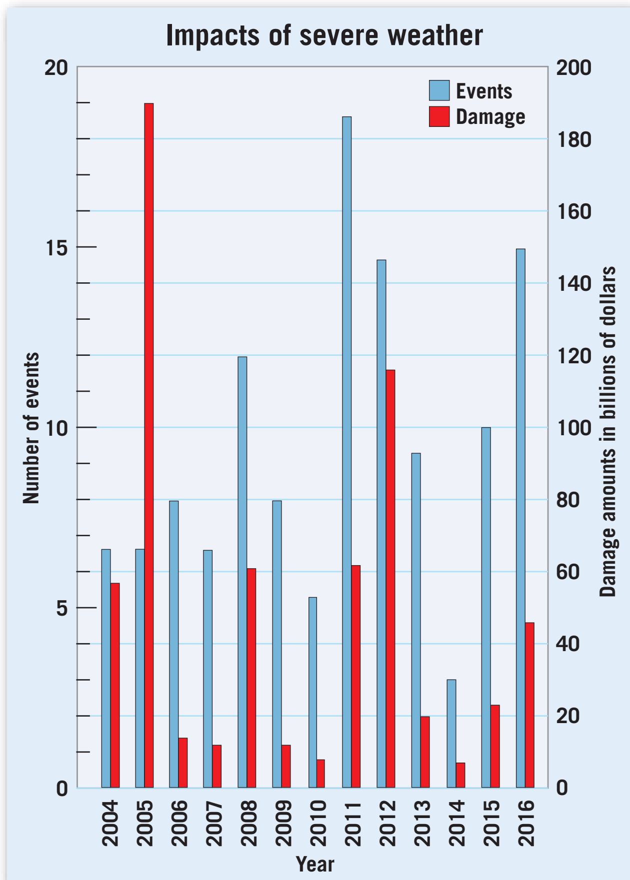
Natural hazards are a part of living on Earth. Every day they adversely affect millions of people worldwide and are responsible for staggering damages. Some, such as earthquakes and volcanic eruptions, are geologic in nature. Many others are related to the atmosphere.

For most people, severe weather events are far more fascinating than ordinary weather phenomena. A spectacular lightning display generated by a severe thunderstorm can elicit both awe and fear. Of course, hurricanes and tornadoes attract a great deal of much-deserved attention. A single tornado outbreak or hurricane can cause billions of dollars in property damage, much human suffering, and many deaths. The chapter-opening satellite image of Hurricane Sandy and the tornado damage depicted in **Figure 1.5** are good examples of such severe weather. Severe storms are covered extensively in Chapters 10 and 11.

Other atmospheric hazards also adversely affect us. Some are storm related, such as blizzards, hail, and freezing rain. Others are not direct results of storms. Heat waves, cold waves, fog, wildfires, and drought are important examples. In some years, the loss of human life due to excessive heat or bitter cold exceeds that caused by all other weather events combined. Although severe storms and floods usually generate more attention, droughts can be just as devastating and carry an even bigger price tag, while extreme heat is the number-one killer worldwide.

Between 2004 and 2016, the United States experienced 102 weather-related disasters in which overall damages and costs reached or exceeded $1 billion (**Figure 1.6**). In addition to taking more than 4100 lives, these events exacted economic costs that exceeded $600 billion! Every day our planet experiences an incredible assault by the atmosphere, so it is important to develop an awareness and understanding of these significant weather events.

▲ **Figure 1.5 Impacts of severe weather** Tornado damage to a grain elevator in Eureka, Kansas, July 8, 2016.



▲ **Figure 1.6 Billion-dollar weather events** Between 2004 and 2016, the United States experienced 102 weather-related disasters in which overall damages and costs reached or exceeded $1 billion. The blue bar graph shows the number of events that occurred each year, and the red bar graph shows damage amounts in billions of dollars (adjusted to 2016 dollars). The total losses for these events exceeded $600 billion! (Data from NOAA)

CONCEPT CHECKS 1.1

- Define *meteorology*. Define and distinguish weather and climate.
- List the basic elements of weather and climate.
- List five storm-related atmospheric hazards and three atmospheric hazards that are not directly storm related.

1.2 The Nature of Scientific Inquiry

- **Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.**

Developing an understanding of how science is done and how scientists work is an important theme in this book. As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Science is a process of producing knowledge. The process depends both on making careful observations and on creating explanations that make sense of the observations. The types of data that are collected often help to answer a well-defined question about the natural world, such as "Why does fog more often develop on cool clear nights, rather than warm overcast nights?" or "What causes rain to form in one cloud type, but not in another?"

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then to use the knowledge gained to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by understanding the forces that influence the movement of air, meteorologists can predict the approximate time and place of the passage of a cold front, which causes temperatures to drop.

Hypothesis

A scientific **hypothesis** is a proposed explanation for a certain phenomenon that occurs in the natural world. For such an explanation to be considered a hypothesis, it must be *testable*. Therefore, before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. This process requires that *predictions* can be made based on the hypothesis being considered. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. More detailed astronomical observations disproved this hypothesis.

A hypothesis is a proposed explanation for a certain phenomenon that occurs in the natural world.

Theory

When a hypothesis has survived extensive scrutiny and when competing hypotheses have been eliminated, it may be elevated to the status of a scientific **theory**. In everyday language, we may say that something is "only a theory." But among the scientific community, a theory is a well-tested and widely accepted view that best explains certain observable facts.

Some theories that are extensively documented and extremely well supported by data are comprehensive in scope. An example from the Earth sciences is the theory of plate tectonics, which provides the framework for understanding the origins of mountains, earthquakes, and volcanic activity. It also explains the evolution of continents and ocean basins through time. As you will see in Chapter 14, this theory also helps us understand some important aspects of climate change through long spans of geologic time.

A scientific theory is a well-tested and widely accepted view that the scientific community agrees best explains certain observable facts.

Scientific Inquiry

The processes just described, in which scientists gather data through observations and formulate scientific hypotheses and theories, is called the *scientific method*. Contrary to popular belief, the scientific method is not a standard recipe that scientists apply in a routine manner to unravel the secrets of our natural world. Rather, it is an endeavor that involves creativity and insight. Rutherford and Ahlgren put it this way: "Inventing hypotheses or theories to imagine how the world works and then figuring out how they can be put to the test of reality is as creative as writing poetry, composing music, or designing skyscrapers."*

Scientists have no fixed path that leads unerringly to scientific knowledge. Nevertheless, most scientific investigations involve the following:

- A question is raised about the natural world.
- Scientific data that relate to the question are collected (Figure 1.7).
- Questions that relate to the data are posed, and one or more working hypotheses that may answer these questions are proposed.
- Observations, experiments, and models are developed to test the hypotheses.
- The hypotheses are accepted, modified, or rejected, based on extensive testing.
- Data and results are shared with the scientific community for critical examination and further testing.

Some scientific discoveries result from purely theoretical ideas that stand up to extensive examination. Some researchers use high-speed computers to simulate what is happening in the "real" world. These models are useful for dealing with natural processes that occur on very long time scales or that take place in extreme or inaccessible locations. Still other scientific advancements have been made when something totally unexpected happened during an experiment. These serendipitous discoveries are more than pure luck; as the nineteenth-century French scientist Louis Pasteur said, "In the field of observation, chance favors only the prepared mind."**

Scientific knowledge is acquired through several avenues, so it might be best to describe the nature of scientific inquiry as the

* F. James Rutherford and Andrew Ahlgren, *Science for All Americans* (New York: Oxford University Press, 1990), p. 7.

** Louis Pasteur, quoted in *Science, History and Social Activism*, edited by Everett Mendelsohn, Garland E. Allen, and Roy M. MacLeod (Dordrecht: Springer, 2001), p. 134.

methods of science rather than *the* scientific method. In addition, it should always be remembered that even the most compelling scientific theories are still simplified explanations of the natural world.

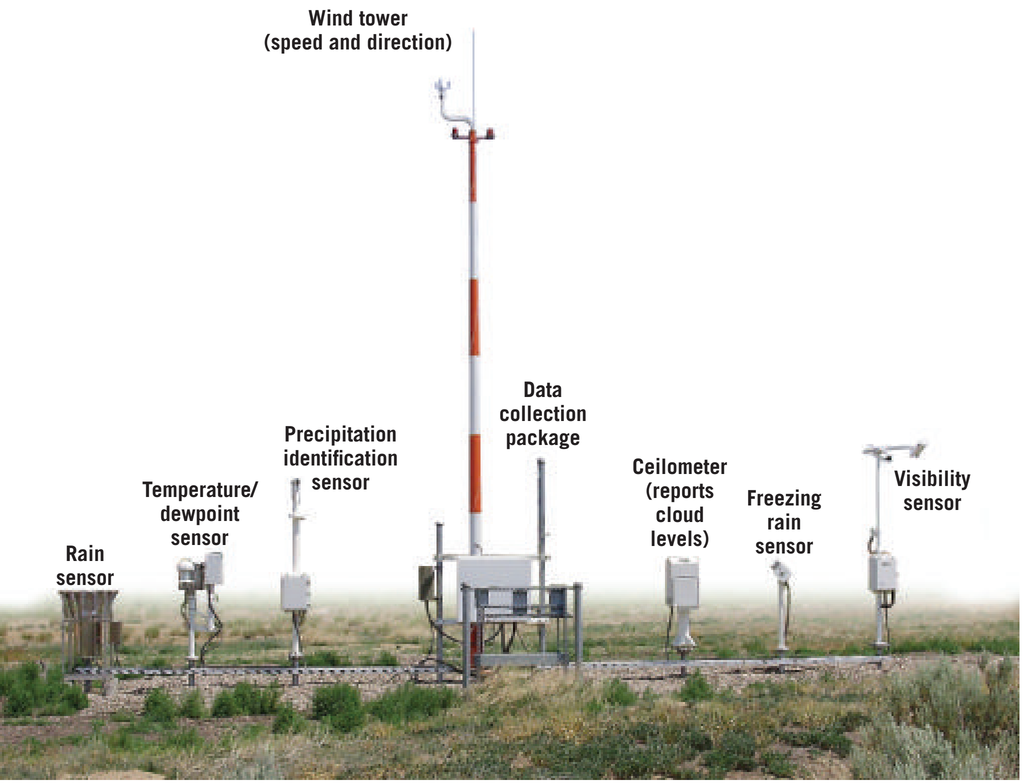
You might have wondered . . .

How do a hypothesis and a theory differ from a scientific law?

A *scientific law* is a basic principle that describes a particular behavior of nature that is generally narrow in scope and can be stated briefly—often as a simple mathematical equation. Because scientific laws have been shown time and time again to be consistent with observations and measurements, they are rarely discarded but may require modifications to fit new findings. For example, Newton's laws of motion are still useful for everyday applications (NASA uses them to calculate satellite trajectories), but they do not work at velocities approaching the speed of light. Einstein's theory of relativity is instead applied in these circumstances.

CONCEPT CHECKS 1.2

- How is a scientific hypothesis different from a scientific theory?
- Summarize the basic steps followed in many scientific investigations.



▲ **Figure 1.7 Observation and measurement are basic parts of scientific inquiry** Automated observing systems, like the one shown, are designed to measure cloud coverage; take temperature and dew-point measurements; determine wind speed and direction; and even record present weather—such as whether it is raining or snowing.

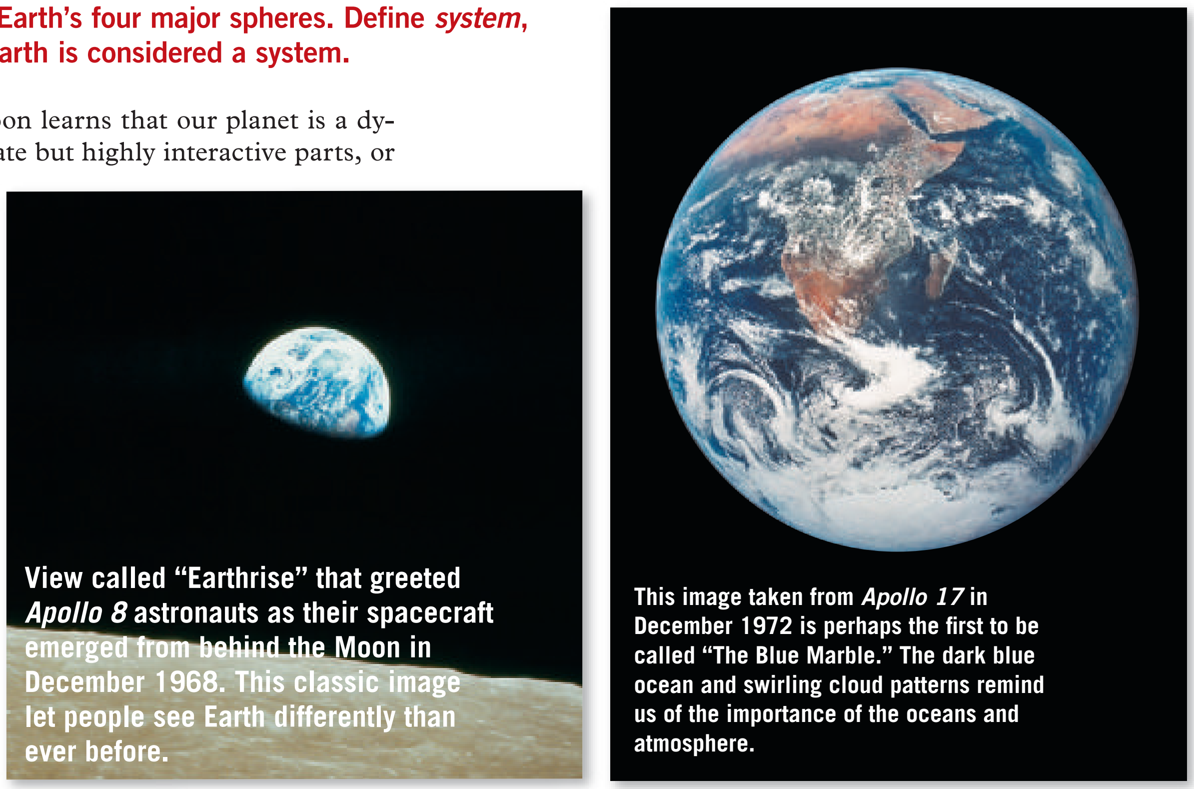
1.3 Earth as a System

- **List and describe Earth's four major spheres. Define *system*, and explain why Earth is considered a system.**

Anyone who studies Earth soon learns that our planet is a dynamic body with many separate but highly interactive parts, or *spheres*. The atmosphere, hydrosphere, biosphere, and lithosphere, along with all of their components, can be studied separately. However, the parts are *not* isolated. Each is related in many ways to the others, producing a complex and continuously interacting whole that we call the *Earth system*.

Earth's Spheres

The images in Figure 1.8 are classics because, for the first time, they let humanity see Earth differently



View called "Earthrise" that greeted *Apollo 8* astronauts as their spacecraft emerged from behind the Moon in December 1968. This classic image let people see Earth differently than ever before.

This image taken from *Apollo 17* in December 1972 is perhaps the first to be called "The Blue Marble." The dark blue ocean and swirling cloud patterns remind us of the importance of the oceans and atmosphere.

▲ **Figure 1.8 Two classic views of Earth from space** from ever before. These photos profoundly altered our conceptualizations of Earth and remain powerful images decades after they were first viewed. Seen from space, Earth is breathtaking in its beauty and startling in its solitude. The images remind us that our home is, after all, a planet—small, self-contained, and in some ways even fragile. Bill Anders, the *Apollo 8* astronaut who took the "Earthrise" photo, expressed it this way: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

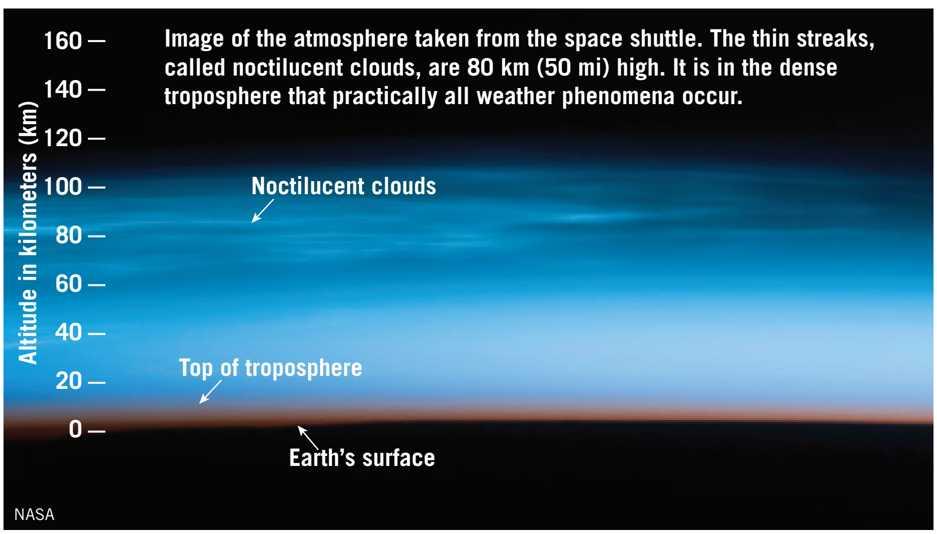
▲ **Figure 1.9 Interactions among Earth's spheres** The shoreline is one obvious example of an *interface*—a common boundary where different parts of a system interact. In this scene, ocean waves (*hydrosphere*) that were created by the force of moving air (*atmosphere*) break against a rocky shore (*lithosphere*).

The closer view of Earth from space shown in Figure 1.8 helps us appreciate why the physical environment is traditionally divided into three major parts: Earth's gaseous envelope, the *atmosphere*; the water portion of our planet, the *hydrosphere*; and Earth's solid outer layer, the *lithosphere*. It should be emphasized that our environment is highly integrated and is not dominated by air, water, or rock alone. Instead, the *biosphere*, the life-forms on our planet, extends into each of the three physical realms and is an equally integral part of the planet.

Moreover, the interactions among Earth's four spheres are incalculable. Figure 1.9 provides one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air, and these spheres in turn support life-forms in and near the water. In this scene, ocean waves created by the drag of air moving across the water are breaking against the rocky shore. The force of water, in turn, erodes the shoreline.

The Earth can be divided into four spheres: the *atmosphere* (air), the *hydrosphere* (water), the *lithosphere* (rock), and the *biosphere* (life-forms).

The Atmosphere Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (Figure 1.10). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth, the atmosphere is a very shallow layer. This thin blanket of air is nevertheless an integral part of the planet. It not only provides the air we breathe, but also acts to protect us from the dangerous radiation emitted by the Sun.

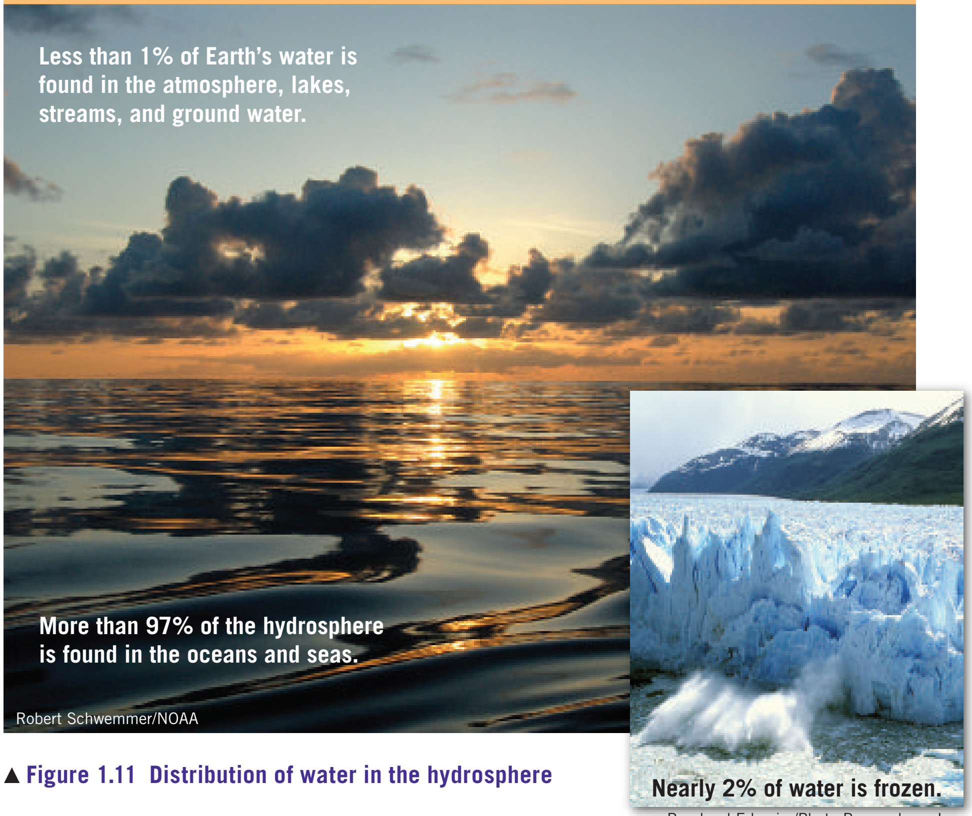


▲ **Figure 1.10 The atmosphere, an integral part of the planet**

Furthermore, the energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call *weather*. If, like the Moon, Earth had no atmosphere, our planet would not only be lifeless, but many of the processes and interactions that make the surface such a dynamic place could not operate.

The Hydrosphere More than anything else, water makes Earth unique. The **hydrosphere** is a dynamic mass that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean

HYDROSPHERE



▲ **Figure 1.11 Distribution of water in the hydrosphere**

is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface (**Figure 1.11**). The hydrosphere also includes the freshwater found in clouds, streams, lakes, and glaciers, as well as that found underground. Although these latter sources constitute only a tiny fraction of the total, they are much more important than their meager percentage indicates. Clouds, of course, play a vital role in many weather and climate processes. In addition, clouds provide the rainfall so essential to life on land.

The Lithosphere Beneath the atmosphere and the ocean is Earth's rocky outer layer, called the **lithosphere**. The surface of the lithosphere is very uneven and contains high mountainous topography, as well as low areas such as Death Valley—portions of which lie below sea level. Sometimes the lithosphere is referred to as the *geosphere*, in which case scientists include Earth's mantle and core in its description.

Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered rock debris (lithosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between the solid particles.

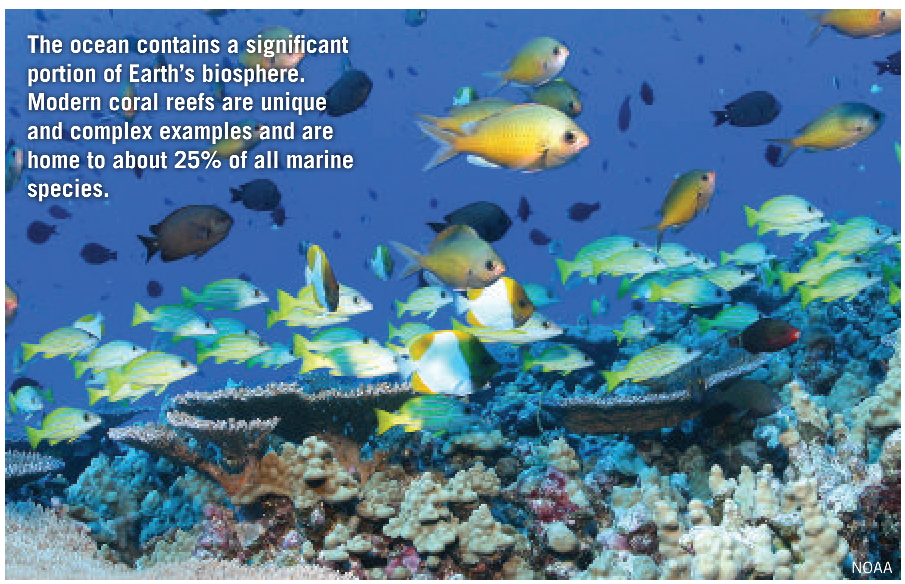
The Biosphere The **biosphere** includes all life on Earth, including the vast oceans (**Figure 1.12**). Plants and animals depend on the physical environment for the basics of life. However, organisms do more than just respond to their physical environment. Through countless interactions, life-forms help maintain and alter their physical environment. Without life, the makeup and nature of the atmosphere, hydrosphere, and lithosphere would be very different.

The Earth System

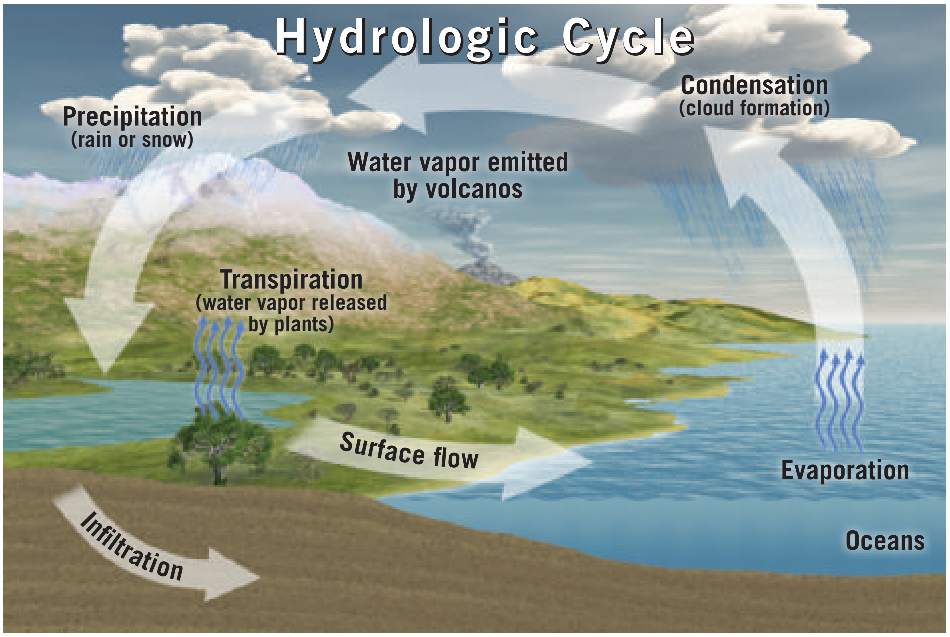
Scientists have recognized that to more fully understand our planet, they must learn how its individual components (air, water, land, and life-forms) are interconnected. This endeavor aims to study Earth as a *system*. A **system** is a collection of numerous interacting parts, or *subsystems*, that form a complex whole. Using an interdisciplinary approach, scientists attempt to understand and address many of our global environmental problems.

Most of us hear and use the term *system* frequently. We may service our car's cooling *system*, make use of the city's transportation *system*, and participate in the political *system*. A news report might inform us of an approaching weather *system*. Further, we know that Earth is just a small part of a larger system known as the *solar system*.

A system is a collection of interacting, or interdependent, parts that form a complex whole.



▲ **Figure 1.12 The biosphere includes all life-forms**



▲ **Figure 1.13 The hydrologic cycle** Water readily changes state from liquid, to gas (vapor), to solid at the temperatures and pressures occurring on Earth. This cycle traces the movements of water among Earth's four spheres. It is one of many subsystems that collectively make up the Earth system.

Earth as a System The Earth system has a nearly endless array of subsystems in which matter is recycled over and over again. One familiar loop, or subsystem, is the *hydrologic cycle*. It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and lithosphere (**Figure 1.13**). Water enters the atmosphere through evaporation from Earth's surface and transpiration from plants. Water vapor (water in the gaseous state) condenses in the atmosphere to form clouds, which in turn produce precipitation that falls back to Earth's surface. Some of the rain that falls onto the land infiltrates (soaks into the ground) and is later taken up by plants or is stored as groundwater, while some flows across the surface toward the ocean.

The parts of the Earth system are linked so that a change in one part can produce changes in any or all of the other parts. For example, during most winter seasons, moisture evaporates from the Pacific Ocean and subsequently falls as rain in the hills of southern California. Sometimes the rainfall is heavy enough to trigger destructive debris flows (**Figure 1.14**). The processes that move water from the hydrosphere to the atmosphere and then to the lithosphere have a profound impact on the physical environment and on the plants and animals (including humans) that inhabit the affected regions.

► **Figure 1.14 Heavy rains trigger debris flow** Vehicles trapped by a mudslide on California Highway 58 near Mojave, California, October 16, 2015, following torrential rains. This image provides an example of interactions among different parts of the Earth system.

Humans are *part of* the Earth system, a system in which the living and nonliving components are profoundly interconnected. Therefore, our actions in one sphere can produce changes in all the other spheres. When we burn gasoline and coal, dispose of wastes, and clear the land, we cause other parts of the system to respond, often in unforeseen ways. Throughout this book, you will learn about some of Earth's subsystems, including the hydrologic system and the climate system. Remember that these components *and we humans* are all part of the complex interacting whole we call the Earth system.

What Powers the Earth System? The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, in the hydrosphere, and at Earth's surface. Weather and climate, ocean circulation, and erosional processes are driven by energy from the Sun. Earth's interior is the second source of energy. Heat remaining from the planet's formation, as well as heat that is continuously generated by radioactive decay, powers the internal processes that produce volcanoes, earthquakes, and mountains.

CONCEPT CHECKS 1.3

- List and briefly define the four spheres that constitute the Earth system.
- What is a system? List three examples.
- What are the two sources of energy for the Earth system?

1.4 Composition of the Atmosphere

■ **List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically.**

Sometimes the term **air** is used as if it were a specific gas, but it is not. Rather, air is a *mixture* of many discrete gases, each with its own physical properties, in which varying quantities of tiny solid and liquid particles are suspended. The composition of air is not constant; it varies from time to time and from place to place (**Box 1.1**). If the water vapor, dust, and other variable components were removed from the atmosphere, we would find that its makeup is very stable up to an altitude of about 80 kilometers (50 miles).

Air is a *mixture* of many gases, each with its own physical properties, in which tiny solid and liquid particles are suspended.

Nonvariable Components

As you can see in **Figure 1.15**, two gases—nitrogen and oxygen—make up about 99 percent of the volume of clean, dry air. Although these gases are the most plentiful components of the atmosphere and are of great significance to life on Earth, they are of little or no importance in affecting weather phenomena. The remaining 1 percent of dry air is mostly the inert gas argon (0.93 percent) plus tiny quantities of other gases listed in Figure 1.15.

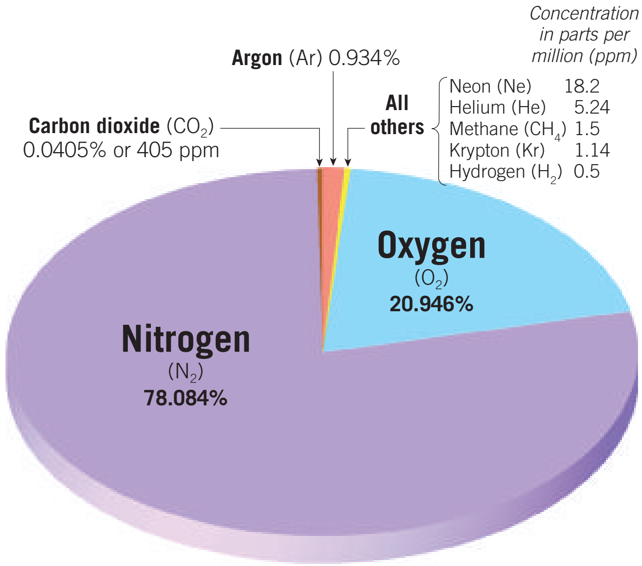
Two gases—nitrogen and oxygen—make up about 99 percent of the volume of clean, dry air.

Variable Components

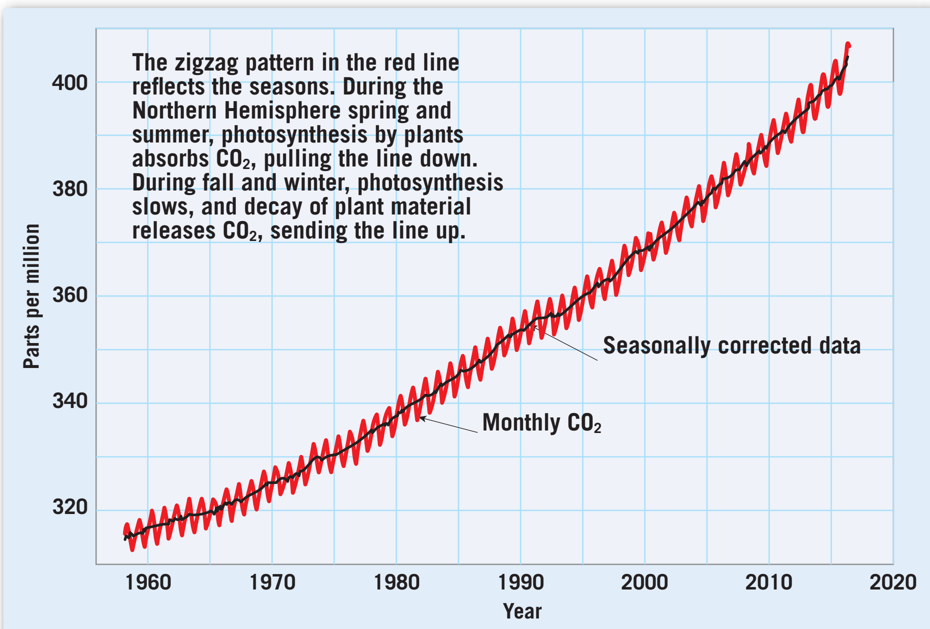
Many of the gases and particles that make up air vary significantly from time to time and place to place. Important examples include carbon dioxide, water vapor, aerosols, and ozone. Although usually present in small percentages, they can significantly affect weather and climate.

Carbon Dioxide Carbon dioxide, a gas present in only minute amounts (0.0400 percent, or 400 parts per million [ppm]), is nevertheless an important constituent of air. Carbon dioxide is of great interest to meteorologists because it is an efficient absorber of energy and thus influences the heating of the atmosphere. Although the proportion of carbon dioxide in the atmosphere is relatively uniform from place to place and at different heights in the atmosphere, its percentage has been rising steadily for more than a century. **Figure 1.16** is a graph that shows the growth in atmospheric CO_2 since 1958. Much of this rise is attributed to the burning of ever-increasing quantities of fossil fuels, such as coal and oil. Some of this additional carbon dioxide is absorbed by the ocean or is used by plants, but more than 40 percent remains in the air. Estimates project that by sometime in the second half of the twenty-first century, atmospheric carbon dioxide will be twice as high as pre-industrial levels.

Most atmospheric scientists agree that increased carbon dioxide concentrations have contributed to a warming of Earth's atmosphere over the past several decades and will



▲ **Figure 1.15 Composition of the atmosphere** Proportional volume of gases composing dry air. Nitrogen and oxygen obviously dominate.



▲ **SMARTFIGURE 1.16 Monthly CO_2 concentrations** Atmospheric CO_2 has been measured at Mauna Loa Observatory, Hawaii, since 1958. There has been a consistent increase since monitoring began.

BOX 1.1 Origin and Evolution of Earth's Atmosphere

The air we breathe is a stable mixture of mainly nitrogen and oxygen along with small amounts of other gases, including argon, carbon dioxide, and water vapor. However, our planet's original atmosphere 4.6 billion years ago was substantially different.

Earth's Primitive Atmosphere

Early in Earth's formation, the planet's atmosphere likely consisted of gases most common in the early solar system: hydrogen, helium, methane, ammonia, carbon dioxide, and water vapor. The lightest of these gases, hydrogen and helium, escaped into space because Earth's gravity was too weak to hold them. Most of the remaining gases were probably largely scattered into space by strong *solar winds* (vast streams of particles) from the young active Sun.

Earth's first enduring atmosphere was generated by a process called *outgassing*, through which gases trapped in the planet's interior are released. Outgassing from hundreds of active volcanoes remains an important planetary function worldwide (**Figure 1.A**). However, early in Earth's history, when the planet's interior experienced massive heating and fluidlike motion, the gas output must have been immense. Our understanding of modern volcanic eruptions indicates that Earth's early atmosphere probably consisted of mostly water vapor, carbon dioxide, and sulfur dioxide, with minor amounts of other gases and minimal nitrogen.

Equally important, molecular oxygen (O_2) was not present in Earth's atmosphere in appreciable amounts for at least the first 2 billion years of Earth history. Molecular oxygen is often called "free oxygen" because it consists of oxygen atoms that are not bound to other elements, such as hydrogen (in water molecules, H_2O) or carbon (in carbon dioxide, CO_2).

Oxygen in the Atmosphere

As Earth's surface cooled, water vapor condensed to form clouds, and torrential rains began to fill low-lying areas that eventually became the oceans. In those oceans, nearly 3.5 billion years ago, primitive bacteria known as *cyanobacteria* (once called blue-green algae) developed the ability to carry out photosynthesis and began to release oxygen into the water. *Photosynthesis* is the production of energy-rich molecules of sugar from molecules of carbon dioxide (CO_2) and water (H_2O), using sunlight as the energy source. The sugars (glucose and other sugars) generated by photosynthesis are used in metabolic processes by living things, and the by-product of photosynthesis is molecular oxygen.

Initially, the newly released oxygen was readily consumed by chemical reactions with other atoms and molecules (particularly iron) in the ocean. Once the available iron satisfied its need for oxygen and as the number of oxygen-generating organisms increased, oxygen molecules began to build up in the atmosphere. Chemical analyses of rocks suggest that a significant amount of oxygen appeared in the atmosphere as early as 2.3 billion years ago. During the following billion years, oxygen levels in the atmosphere probably fluctuated but remained below current levels. Then, roughly 550 million years ago, the level of free oxygen in the atmosphere began to increase once again. The availability of abundant oxygen in the atmosphere contributed to the proliferation of aerobic life-forms (oxygen-consuming organisms).

Another significant benefit of this "oxygen explosion" is that oxygen molecules (O_2) readily absorb ultraviolet radiation and rearrange themselves to form *ozone* (O_3). Today, ozone is concentrated above the surface in a layer called the *stratosphere*, where it absorbs much of the Sun's ultraviolet radiation that strikes the upper atmosphere. For the first time, Earth's surface was protected from this type of solar radiation, which is particularly harmful to DNA. Marine organisms had always been shielded from ultraviolet radiation by the oceans, but the development of the atmosphere's protective ozone layer made the continents more hospitable.

Apply What You Know

1. What was the source of the gases that composed Earth's first enduring atmosphere?
2. What was the source of the atmosphere's first free oxygen?

Video
The Influence of Volcanic Ash

▼ **Figure 1.A Outgassing** Earth's first enduring atmosphere was formed by a process called *outgassing*, which continues today, from hundreds of active volcanoes worldwide.

continue to do so in the decades to come. The magnitude of such temperature changes is uncertain and depends partly on the quantities of CO_2 contributed by human activities in the years ahead. The role of carbon dioxide in the atmosphere and its possible effects on climate are examined in more detail in Chapters 2 and 14.

Water Vapor You are probably familiar with the term *humidity* from watching weather reports on TV. *Humidity* refers to the amount of water vapor in the air. As you will learn in Chapter 4, there are several ways to express humidity. The amount of water vapor in the air varies considerably, from practically none to up to about 4 percent by volume. Why is such a small fraction of the atmosphere so significant? The fact that water vapor is the source of all clouds and precipitation would be enough to explain its importance. However, water vapor has other roles. Like carbon dioxide, water vapor absorbs heat given off by Earth as well as some solar energy. It is therefore important when we examine the heating of the atmosphere and the movement of energy on Earth.

When water changes from one state to another (see Figure 4.3, page 86), it absorbs or releases heat. This energy is termed *latent heat*, which means "hidden heat." As we shall see in later chapters, water vapor in the atmosphere transports this latent heat from one region to another, and it is the energy source that helps drive many storms.

Aerosols The movements of the atmosphere are sufficient to keep a large quantity of solid and liquid particles suspended within it. These tiny solid and liquid particles are collectively called **aerosols**. Although visible dust sometimes obscures the sky, these relatively large particles are too heavy to stay in the air very long. However, many particles are microscopic and remain suspended for considerable periods of time. They may originate from many sources, both natural and human made, and include sea salts from breaking waves, fine soil blown into the air, smoke and soot from fires, pollen and microorganisms lifted by the wind, ash and dust from volcanic eruptions, and more (**Figure 1.17**).

Aerosols are most numerous in the lower atmosphere near their primary source, Earth's surface. Nevertheless, the upper atmosphere is not free of them: Some particles are carried to great heights by rising currents of air, while others are contributed by meteoroids that disintegrate as they pass through the atmosphere.

From a meteorological standpoint, these tiny, often invisible particles are important. First, many act as surfaces on which water vapor may condense, a critical function in the formation of clouds and fog. Second, aerosols can absorb or reflect incoming solar radiation. Thus, when an air pollution episode is occurring or when ash fills the sky following a volcanic eruption, the amount of sunlight reaching Earth's surface can be measurably reduced. Finally, aerosols contribute to an optical

A. B.

▲ **Figure 1.17 Aerosols A.** The satellite image shows two examples of aerosols. First, a large dust storm is blowing across northeastern China toward the Korean Peninsula. Second, a dense haze toward the south (bottom center) is human-generated air pollution. **B.** As the photo on the right shows, dust in the air can cause sunsets to be especially colorful.

BOX 1.2 Ozone Depletion: A Global Issue

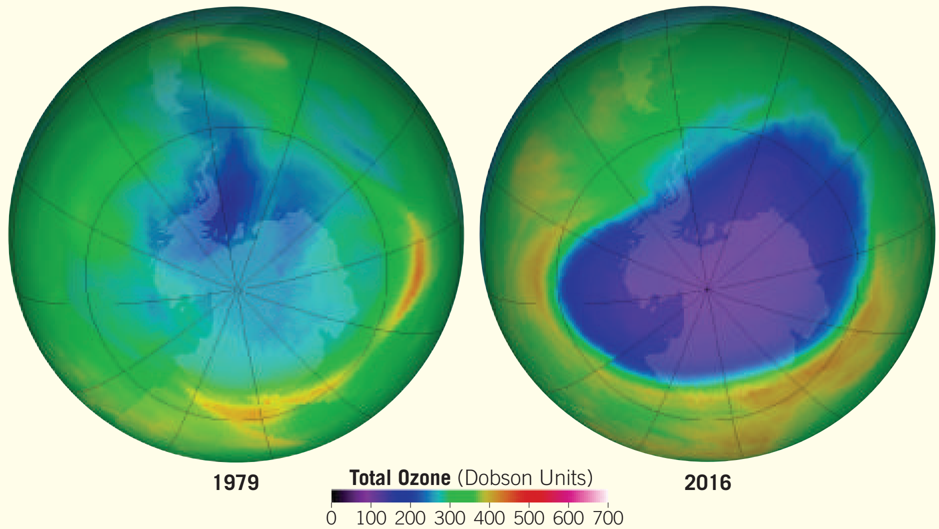
Although stratospheric ozone is concentrated high above Earth's surface, it is vulnerable to human activities. Manufactured chemicals break up ozone molecules in the stratosphere, weakening our shield against UV rays. Measurements over the past three decades confirm that ozone depletion is occurring worldwide and is especially pronounced above Earth's poles. **Figure 1.B** shows this effect over the South Pole.

Over the past 80 years, people have unintentionally placed the ozone layer in jeopardy by polluting the atmosphere. The most significant of the offending chemicals are known as *chlorofluorocarbons (CFCs)*. Developed in the 1930s, CFCs were used as coolants for air-conditioning and refrigeration equipment, cleaning solvents, and propellants for aerosol sprays.

Because CFCs are practically inert (not chemically active) in the lower atmosphere, some of these gases gradually make their way up to the ozone layer, where sunlight separates the CFCs into their constituent atoms. The release of a single chlorine atom, which acts as a catalyst, can be responsible for destroying thousands of ozone molecules.

Because ozone filters out most of the UV radiation from the Sun, a decrease in atmospheric ozone permits more of these harmful wavelengths to reach Earth's surface. UV radiation's most serious threat to human health is an increased risk of skin cancer. Increased UV radiation can also impair the human immune system and promote cataracts, a clouding of the eye lens that reduces vision and may cause blindness if not treated.

On September 28, 2016, the ozone hole extended across an area nearly three times the size of the continental United States.



▲ **SMARTFIGURE 1.B Antarctic ozone hole** The two satellite images show ozone distribution in the Southern Hemisphere on the days in September 1979 and 2016 when the ozone hole was largest. The purple and blue colors are where there is the least ozone, and the yellows and reds are where there is more ozone.

Animation
Ozone Hole

In response to this problem, an international agreement known as the *Montreal Protocol* was developed in 1987 to eliminate the production and use of CFCs. More than 190 nations eventually ratified the treaty. Although relatively strong action has been taken, CFC levels in the atmosphere will not drop rapidly. Once CFC molecules are in the atmosphere, they can take many years to reach the ozone layer, and once there, they can remain active for decades. This does not promise a near-term reprieve for the ozone layer. Nevertheless, the Montreal Protocol represents a positive international response to solve this global problem.

Apply What You Know

1. What are CFCs, and what is their connection to ozone depletion?
2. What is the Montreal Protocol, and what did it achieve?

phenomenon we have all observed—the varied hues of red and orange at sunrise and sunset. The photo on the right in Figure 1.17 illustrates this phenomenon.

Ozone Another important component of the atmosphere is **ozone**. It is a form of oxygen that contains three oxygen atoms in each molecule (O_3), unlike the oxygen we breathe, which has two atoms per molecule (O_2). There is very little ozone in the atmosphere; overall, it accounts for just 3 out of every 10 million molecules. Moreover, its distribution is not uniform. It is concentrated in a layer called the *stratosphere*, between 10 and 50 kilometers (6 and 31 miles) above the Earth's surface.

In this altitude range, oxygen molecules (O_2) are split into single atoms of oxygen (O) when they absorb ultraviolet radiation emitted by the Sun. Ozone is then created when a single atom of oxygen (O) and a molecule of oxygen (O_2) collide. This must happen in the presence of a third, neutral molecule that acts as a *catalyst* by allowing the reaction to take place without itself being consumed in the process. Ozone is concentrated in the 10- to 50-kilometer height range because a crucial balance exists there: The ultraviolet radiation from the Sun is sufficient to produce single atoms of oxygen, and enough gas molecules are present to bring about the required collisions.

The presence of this ozone layer in our atmosphere is essential to those of us who are land dwellers. The reason is that ozone absorbs much of the potentially harmful ultraviolet (UV) radiation from the Sun. If ozone did not filter a great deal of the ultraviolet radiation, land areas on our planet would be uninhabitable for most life as we know it. Thus, anything that reduces the amount of ozone in the atmosphere could affect the well-being of life on Earth. Just such a problem is described in **Box 1.2**.

You might have wondered . . .

Isn't ozone some sort of pollutant?

- Although the naturally occurring ozone in the stratosphere is critical to life on Earth, it is considered a pollutant when produced at ground level because it can damage vegetation and harm human health. Ozone is a major component in a noxious mixture of gases and particles called *photochemical smog* formed from pollutants emitted by motor vehicles and industries.

CONCEPT CHECKS 1.4

- What are the two major components of clean, dry air? What proportion does each represent?
- Why is carbon dioxide an important component of Earth's atmosphere? Why are water vapor and aerosols important atmospheric constituents?
- What is ozone? Why is ozone important to life on Earth?

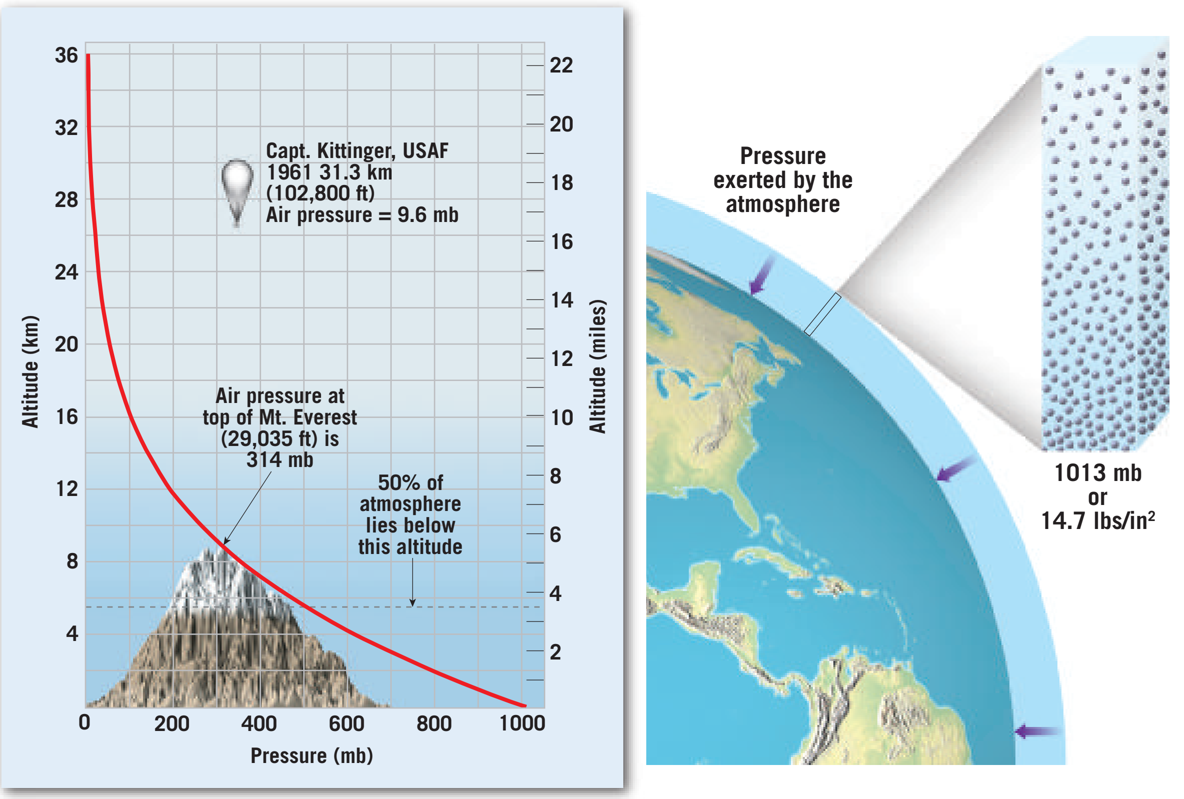
1.5 Vertical Structure of the Atmosphere

- **Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows the thermal structure of the atmosphere.**

When compared to the size of the solid Earth, the envelope of air surrounding our planet is indeed very shallow. To say that the atmosphere begins at Earth's surface and extends upward is obvious. However, where does the atmosphere end, and where does outer space begin? There is no sharp boundary; the atmosphere rapidly thins as you travel away from Earth, until there are too few gas molecules to detect.

Pressure Changes

To understand the vertical extent of the atmosphere, let us examine the changes in atmospheric pressure with height. Atmospheric pressure is simply the weight of the air above. To describe atmospheric pressure, the National Weather Service uses a measure called the *millibar* (mb), which will be



▲ **Figure 1.18 Air pressure changes with altitude** The rate of pressure decrease with an increase in altitude is not constant. Pressure decreases rapidly near Earth's surface and more gradually at greater heights. Put another way, the figure shows that the vast bulk of the gases making up the atmosphere is near Earth's surface and that the gases gradually merge with the emptiness of space.

discussed in detail in Chapter 6. At sea level, the average pressure is slightly more than 1000 millibars. This corresponds to a weight of about 14.7 pounds per square inch. Obviously, the pressure at higher altitudes is less because there is less air (fewer air molecules) above these altitudes (**Figure 1.18**).

Atmospheric pressure is simply the weight of the air above.

One-half of the atmosphere lies below an altitude of 5.6 kilometers (3.5 miles). At about 16 kilometers (10 miles), 90 percent of the atmosphere has been traversed. At an altitude of 100 kilometers, the atmosphere is so thin that the density of air is less than could be found in the most perfect artificial vacuum at the surface. Nevertheless, the atmosphere continues to even greater heights. In fact, traces of our atmosphere extend for thousands of kilometers beyond Earth's surface. Thus, to say where the atmosphere ends and outer space begins is arbitrary and depends on what phenomenon one is studying. It is apparent that there is no sharp boundary.

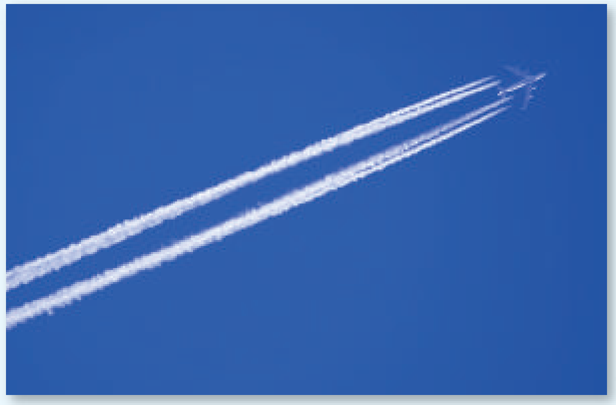
The graphic portrayal of pressure data in Figure 1.18 shows that the rate of pressure decrease is not constant. Rather, air pressure falls at a decreasing rate with an increase in altitude. Put another way, air is highly compressible—that is, the gases that make up air expand with decreasing pressure and become compressed with increasing pressure.

eye on the ATMOSPHERE 1.1

This jet is cruising at an altitude of 10 kilometers (6.2 miles).

Apply What You Know

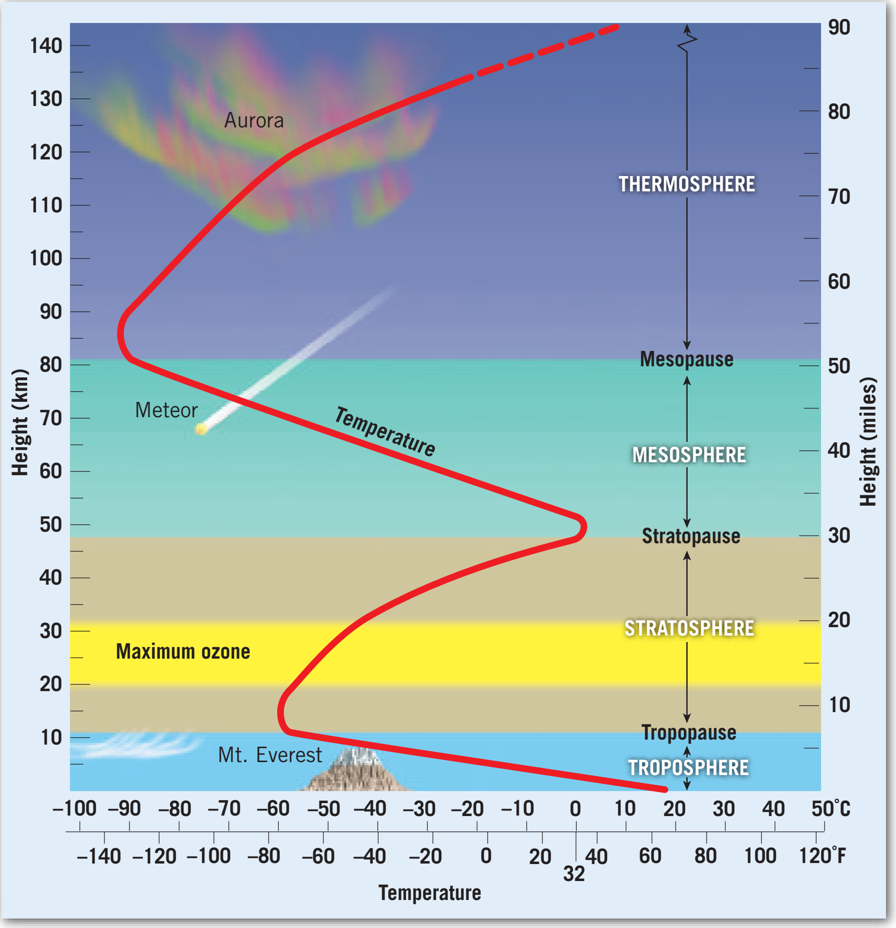
1. Refer to the graph in Figure 1.18. What is the approximate air pressure where the jet is flying?
2. About what percentage of the atmosphere is below the jet (assuming that the pressure at the surface is 1000 millibars)?



Temperature Changes

By the early twentieth century, scientists collecting data obtained from balloons and kites found that the air temperature dropped with increasing height above Earth's surface. This phenomenon is felt by anyone who has climbed a high mountain and is obvious in pictures of snow-capped mountaintops rising above snow-free lowlands (**Figure 1.19**).

◄ **Figure 1.19 Temperature change in the troposphere** Snow-capped mountains and snow-free lowlands are a reminder that temperatures decrease as we go higher in the troposphere.



▲ **Figure 1.20 Thermal structure of the atmosphere** Earth's atmosphere is traditionally divided into four layers, based on temperature.

Scientists once believed that the temperature continued to decrease with height to a value of absolute zero (–273°C) at the outer edge of the atmosphere. In 1902, however, French scientist Leon Philippe Teisserenc de Bort refuted the notion that temperature decreases continuously with an increase in altitude. In studying the results of more than 200 balloon launchings, Teisserenc de Bort found that the temperature leveled off at an altitude between 8 and 12 kilometers (5 and 7.5 miles). Later, the use of balloons and rocket-sounding techniques revealed the temperature structure of the atmosphere up to great heights. Based on these temperature measurements, the atmosphere can be divided vertically into four layers (Figure 1.20). The temperature profile shown in Figure 1.20 represents the average temperature change with altitude. However, the actual temperature profile can be quite variable from one day to the next—particularly in the lower atmosphere.

Troposphere The bottom layer in which we live, where average temperatures decrease with an increase in altitude, is the **troposphere**. The term was coined in 1908 by Teisserenc de Bort and literally means the region where air "turns over," a reference to the appreciable vertical mixing of air in this lowermost zone.

The temperature decrease in the troposphere is called the **environmental lapse rate**. Its average value is 6.5°C per kilometer (3.5°F per 1000 feet), a figure known as the *normal lapse rate*. It should be emphasized, however, that the environmental lapse rate is not a constant but rather can be highly variable and must be regularly measured. Radiosondes are used to measure the actual environmental lapse rate, as well as gather information about vertical changes in air pressure, wind, and humidity. A **radiosonde** is an instrument package that is attached to a balloon and transmits data by radio as it ascends through the atmosphere (Figure 1.21). The environmental lapse rate can vary over the course of a day as a result of fluctuations in weather, as well as seasonally and from place to place. Sometimes shallow layers where temperatures actually increase with height are observed in the troposphere. Such reversals, called **temperature inversions**, are described in greater detail in Chapter 13.

The temperature continues to decrease to an *average* height of about 12 kilometers (7.5 miles), which marks the top of the troposphere, called the **tropopause** (see Figure 1.20). Yet the thickness of the troposphere is not the same everywhere. In the tropics, the tropopause reaches heights in excess of 16 kilometers (10 miles), whereas in polar regions it is lower, varying from about 7 to 8 kilometers (about 5 miles) (Figure 1.22). Warm surface temperatures and highly developed thermal mixing as the warmed air rises are responsible for the greater vertical extent of the troposphere near the equator.

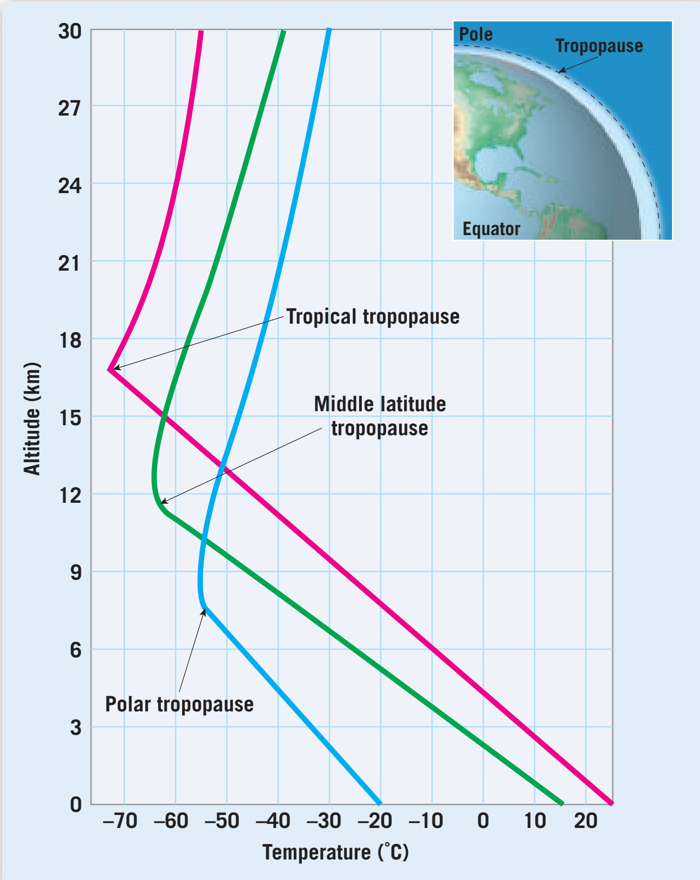
The troposphere is the chief focus of meteorologists because it is in this layer that essentially all important weather phenomena occur. Almost all clouds and certainly all precipitation, as well as all our violent storms, are born in this lowermost layer of the atmosphere. This is why the troposphere is often called the "weather sphere."

The atmosphere is divided into four layers, based on temperature—the *troposphere*, *stratosphere*, *mesosphere*, and *thermosphere*.

Stratosphere Above the troposphere lies the **stratosphere**. In the stratosphere, the temperature at first remains nearly constant to a height of about 20 kilometers (12 miles) before it begins a sharp increase that continues until the **stratopause** is encountered at a height of about 50 kilometers (30 miles) above Earth's surface (see Figure 1.20). The high concentration of ozone in the stratosphere accounts for the rise in temperature observed in this layer. Recall that ozone absorbs ultraviolet radiation from the Sun, which in turn causes its temperature to rise.

Although the troposphere is dominated by large-scale turbulence and mixing, very little vertical mixing occurs in the stratosphere. This is because the stratosphere experiences a temperature inversion, where cold air lies beneath warm air, in contrast to the opposite occurrence in the troposphere.

▲ **Figure 1.21 Radiosonde** This lightweight package of instruments is carried aloft by a small weather balloon. It transmits data on vertical changes in temperature, pressure, and humidity in the troposphere. The troposphere is where practically all weather phenomena occur, so it is very important to have frequent measurements.



▲ **Figure 1.22 Differences in the height of the tropopause** The variation in the height of the tropopause, as shown on the small inset diagram, is greatly exaggerated.

Mesosphere In the third layer, the **mesosphere**, temperatures decrease with height until the **mesopause**, or top of the mesosphere, is reached (see Figure 1.20). This decrease in temperature with height leads to abundant vertical mixing. The mesopause is located about 80 kilometers (50 miles) above the surface, where the average temperature approaches a chilly –90°C (–130°F)—the coldest temperatures anywhere in the atmosphere.

The mesosphere is one of the least explored regions of the atmosphere because it cannot be reached by the highest-flying airplanes and research balloons, nor is it accessible to the lowest-orbiting satellites. Recent technical developments are just beginning to fill this knowledge gap.

Thermosphere The fourth layer extends outward from the mesopause and has no well-defined upper limit. It is the **thermosphere**, a layer that contains only a tiny fraction of the atmosphere's mass. In the extremely rarified air of this outermost layer, temperatures again increase as oxygen and nitrogen atoms absorb very shortwave, high-energy solar radiation (Figure 1.20).

Temperatures rise to extremely high values of more than 1000°C (1800°F) in the thermosphere. But such temperatures are not comparable to those experienced near Earth's surface. **Temperature** is defined in terms of the average speed at which molecules move—the higher the speed, the higher the temperature. Because the gases of the thermosphere are moving at very high speeds, the temperature is very high. But the gases are so sparse that collectively they possess only an insignificant quantity of thermal energy (heat). For this reason, the temperature of a satellite orbiting Earth in the thermosphere is determined chiefly by the amount of solar radiation it absorbs, and not by the high temperature of the almost nonexistent surrounding air. If an astronaut inside were to expose his or her hand, the air in this layer would not feel hot.

The Ionosphere

In addition to the layers defined by vertical variations in temperature, scientists recognize another layer in the atmosphere. Located between 80 and 400 kilometers (50 to 250 miles) above Earth's surface, and thus coinciding with the lower portion of the thermosphere, is an electrically charged layer known as the **ionosphere**. Here molecules of nitrogen and atoms of oxygen

eye on the ATMOSPHERE 1.2

When this weather balloon was launched, the surface temperature was 17°C. It is now at an altitude of 1 kilometer.

Apply What You Know

1. What term is applied to the instrument package being carried aloft by the balloon?
2. In what layer of the atmosphere is the balloon?
3. If average conditions prevail, what air temperature is the instrument package recording? How did you figure this out?

are readily ionized as they absorb high-energy shortwave solar radiation. Ionization is a process in which the affected molecule or atom loses one or more electrons and becomes a positively charged ion, and the electrons set free then travel as electric currents.

As best we can tell, the ionosphere has little impact on our daily weather. But this layer of the atmosphere is the site of one of nature's most interesting spectacles, the **auroras** (Figure 1.23). The *aurora borealis* (northern lights) and its Southern Hemisphere counterpart, the *aurora australis* (southern lights), appear in a wide variety of forms. Sometimes the displays consist of vertical streamers in which there can be considerable movement. At other times, the auroras appear as a series of luminous expanding arcs or as a quiet glow that has an almost foglike quality.

Auroral displays are aligned with Earth's magnetic poles and closely correlated with large solar storms, such as solar flares. Solar flares are massive magnetic storms on the Sun that emit enormous quantities of fast-moving atomic particles. As these charged particles (ions) approach Earth, they are captured by its magnetic field, which in turn guides them toward the magnetic poles. Then, as the ions impinge on the ionosphere, they energize the atoms of oxygen and molecules of nitrogen and cause them to emit light—the glow of the auroras. Because the occurrence of solar storms is closely associated with sunspot activity, auroral displays increase conspicuously at times when sunspots are most numerous.

CONCEPT CHECKS 1.5

- Does air pressure increase or decrease with an increase in altitude? Is the rate of change constant or variable? Explain.
- The atmosphere is divided vertically into four layers based on temperature. List these layers in order from lowest to highest. In which layer does practically all weather occur?
- What is the *ionosphere*? How is it related to the auroras?

► **Figure 1.23 The auroras** The aurora borealis (northern lights), as seen in Alaska. The same phenomenon occurs toward the South Pole, where it is called the aurora australis (southern lights).

CONCEPTS IN REVIEW

1.1 Focus on the Atmosphere

■ **Distinguish between weather and climate, name the basic elements of weather and climate, and list several important atmospheric hazards.**

Key Terms: meteorology weather climate

- Meteorology is the scientific study of the atmosphere. *Weather* refers to the state of the atmosphere at a given time and place. It is constantly changing, sometimes from hour to hour. *Climate* refers to the average weather conditions and the sum of all statistical weather information that helps describe a place or region.
- The most important elements of weather and climate are (1) air temperature, (2) humidity, (3) type and amount of cloudiness, (4) type and amount of precipitation, (5) air pressure, and (6) the speed and direction of the wind.
- Some atmospheric hazards are storm related, such as lightning, blizzards, and hail. Others are not storm related, such as fog, heat waves, and drought.

1.2 The Nature of Scientific Inquiry

■ **Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.**

Key Terms: hypothesis theory

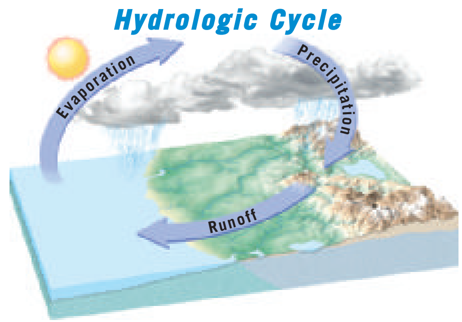
- All science is based on the assumption that the natural world behaves in a consistent and predictable manner. Scientists make careful observations, construct tentative explanations for those observations (hypotheses), and then test those hypotheses with field investigations and laboratory work.
- In science, a theory is a well-tested and widely accepted explanation that the scientific community agrees best fits certain observable facts.

1.3 Earth as a System

■ **List and describe Earth's four major spheres. Define *system*, and explain why Earth is considered a system.**

Key Terms: hydrosphere biosphere atmosphere lithosphere system

- Earth's physical environment is traditionally divided into three major parts: Earth's gaseous envelope, called the atmosphere; the water portion of our planet, called the hydrosphere; and the solid Earth, called the lithosphere. A fourth Earth sphere is the biosphere, the totality of life on Earth.
- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole that is called the Earth system.
- Earth system science uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our planet and its global environmental problems.
- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmosphere, hydrosphere, and at Earth's surface, and (2) heat from Earth's interior that powers the internal processes that produce volcanoes, earthquakes, and mountains.



1.4 Composition of the Atmosphere

■ **List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically.**

Key Terms: air aerosols ozone

- Air is a mixture of many discrete gases, and its composition varies from time to time and place to place. Two nonvariable gases, nitrogen and oxygen, make up 99 percent of the volume of the atmosphere.
- Carbon dioxide (CO_2), a variable gas present in only minute amounts, is an efficient absorber of energy emitted by Earth and thus influences the heating of the atmosphere.
- Water vapor is important because it is the source of all clouds and precipitation. Like carbon dioxide, water vapor can absorb heat emitted by Earth. In the atmosphere, water vapor transports latent ("hidden") heat from place to place and is the energy that helps to drive many storms.
- Aerosols are tiny solid and liquid particles that are important because they may act as surfaces onto which water vapor can condense. They also absorb and reflect incoming solar radiation.
- Ozone, a form of oxygen that combines three oxygen atoms into each molecule (O_3), is a gas concentrated in the stratosphere. Ozone is important to life because it can absorb harmful ultraviolet radiation from the Sun. People have placed Earth's ozone layer in jeopardy by polluting the atmosphere with chlorofluorocarbons (CFCs), which break apart the ozone.

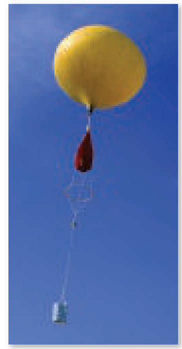
1.5 Vertical Structure of the Atmosphere

■ **Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows the thermal structure of the atmosphere.**

Key Terms: radiosonde stratosphere thermosphere troposphere temperature inversion stratopause temperature environmental lapse rate mesosphere ionosphere tropopause mesopause aurora

- Pressure is the weight of the air above a location. Because air is compressible, pressure decreases at an increasing rate as you go up in the atmosphere.

- Based on temperature, the atmosphere is divided vertically into four layers. The troposphere is the lowermost layer. In the troposphere, temperature usually decreases with increasing altitude. Essentially, all important weather phenomena occur in the troposphere.
- Above the troposphere is the stratosphere, which warms with altitude because of absorption of UV radiation by ozone. In the mesosphere, temperatures again decrease. Upward from the mesosphere is the thermosphere, a layer with only a tiny fraction of the atmosphere's mass and no well-defined upper limit.
- The ionosphere is an electrically charged layer of the atmosphere where molecules of nitrogen and atoms of oxygen are readily ionized as they absorb solar radiation.
- Auroras (the northern and southern lights) occur within the ionosphere. Auroras form as atomic particles ejected from the Sun during solar flare activity enter the atmosphere near Earth's magnetic poles and energize the atoms of oxygen and molecules of nitrogen, causing them to emit light.



EXERCISES AND ONLINE ACTIVITIES

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Review Questions

1. What is meteorology?
2. List some examples of how weather changes.
3. Explain how climate changes.
4. What are some examples of atmospheric hazards?
5. What is a hypothesis? How is a theory different from a hypothesis?
6. Why is the scientific method useful?
7. List the four spheres of Earth, and describe their basic characteristics.
8. How much of Earth's surface is covered by oceans?
9. Briefly explain why is Earth considered a "system."
10. Sketch and describe the hydrologic cycle.
11. List the components of Earth's atmosphere, and indicate which ones are variable.
12. In what ways is water vapor important in the atmosphere?
13. What are aerosols, and what role do they play in the atmosphere?
14. Why is ozone important in the atmosphere?
15. Define *atmospheric pressure*.
16. How does pressure change vertically in the atmosphere?
17. Sketch the typical vertical temperature profile of the atmosphere, and label each layer. List their basic properties.
18. Explain why temperature increases in the stratosphere.
19. How is the ionosphere different from the atmosphere's thermal layers?
20. Explain how an aurora is formed.

Give It Some Thought

1. Determine which statements refer to weather, and which are considered climate.
   a. The baseball game was rained out today.
   b. January is Chicago's coldest month.
   c. North Africa is a desert.
   d. Light rain fell most of the afternoon.
   e. Last evening a tornado ripped through central Oklahoma.
   f. I am moving to southern Arizona because it is warm and sunny.
   g. Thursday's low of –20°C is the coldest temperature ever recorded for that city.
   h. It is partly cloudy.
2. This map shows the mean percentage of sunshine received in the month of November across the 48 contiguous United States.
   a. Does this map relate more to weather or to climate?
   b. If you were to visit Yuma, Arizona, on a day in November, would you *expect* to experience a sunny day or an overcast day?
   c. Might what you actually experience during your visit differ from what you expected? Explain.