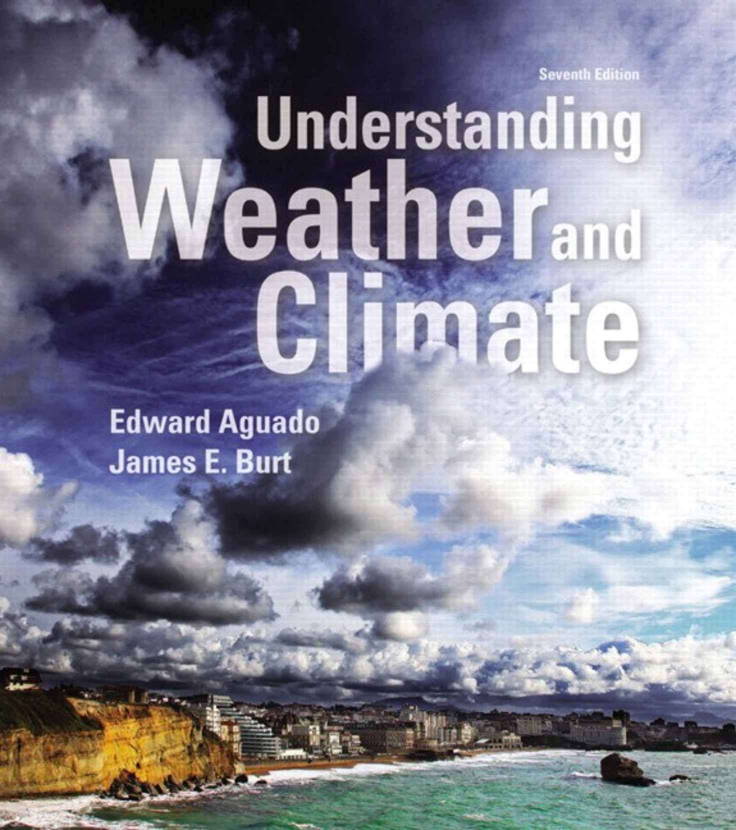

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Understanding Weather and Climate

Edward Aguado
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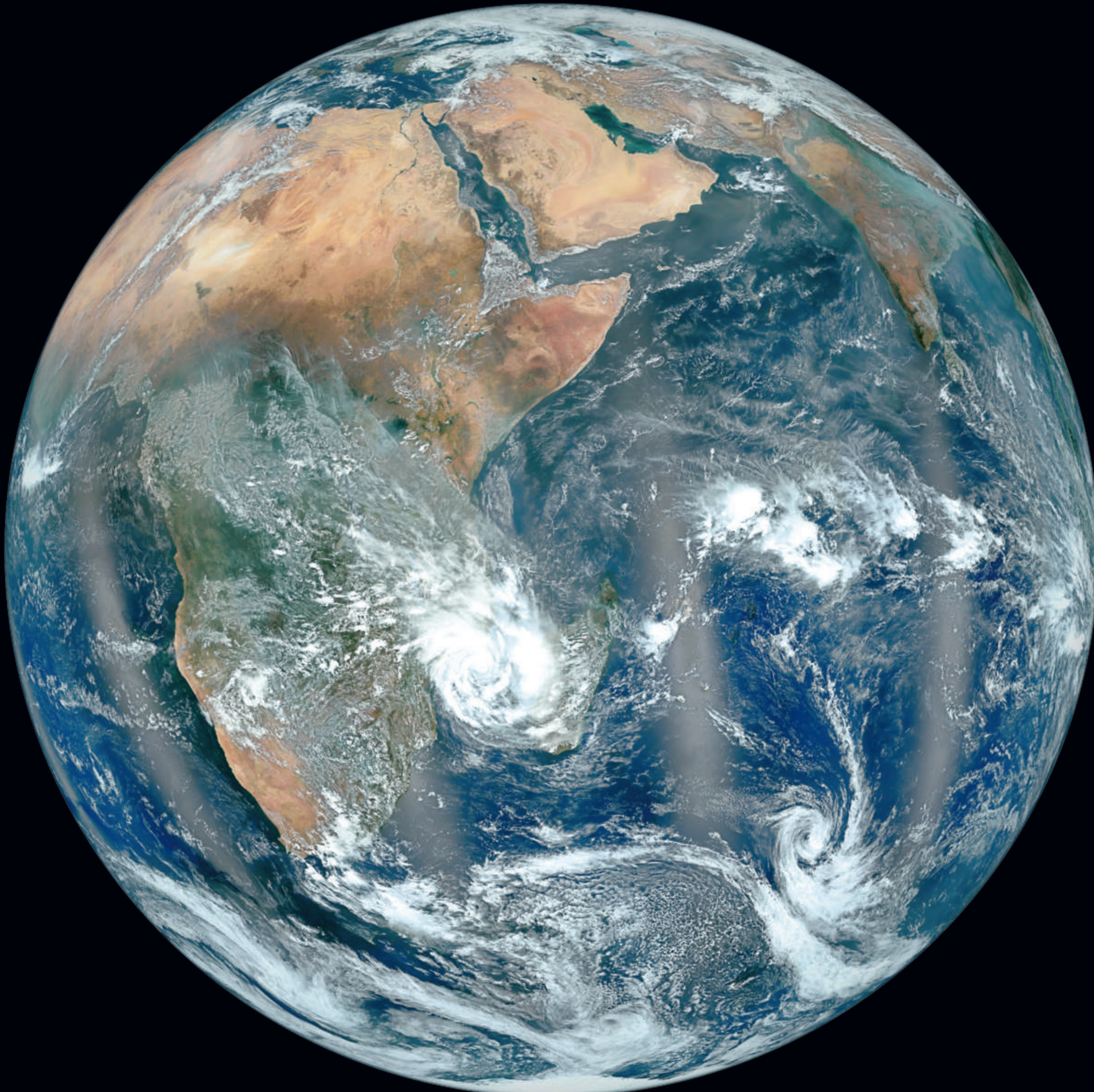
Earth from Space



This image from NASA's Suomi-NPP "Marble" series is centered on the Eastern Hemisphere. The swirling cloud patterns and storm systems reflect not only the distribution of moisture in the atmosphere, but also the transfer of vast amounts of energy among regions of varying temperature and pressure.

Views of our planet from space can help us grasp how the atmosphere, oceans, land, and life itself are all interconnected.

This image shows a region including Africa, the Middle East, and Europe. It is a composite of nighttime images assembled from data acquired by the same Suomi NPP satellite as was used for daylight image, but this view is based on instrumentation that observes light emanating from the ground. Note how strongly major cities show up in the image, as well as flares in the Middle East from the burning of natural gas byproducts from petroleum mining activities.

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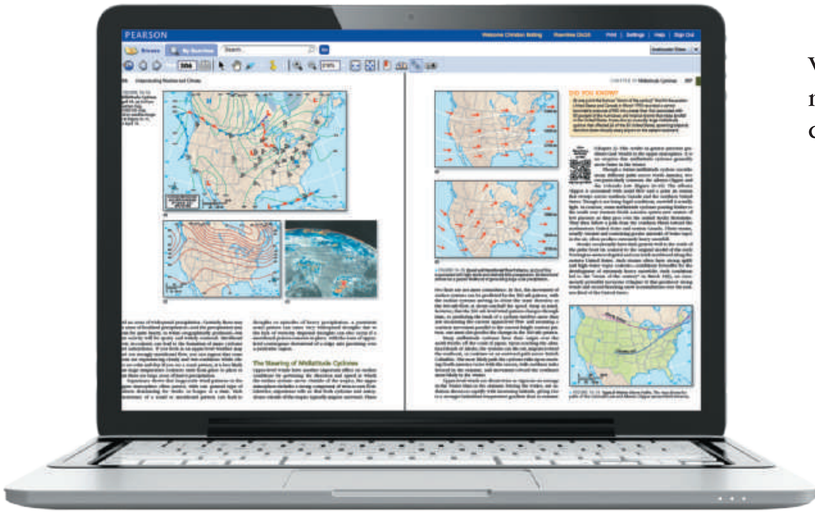

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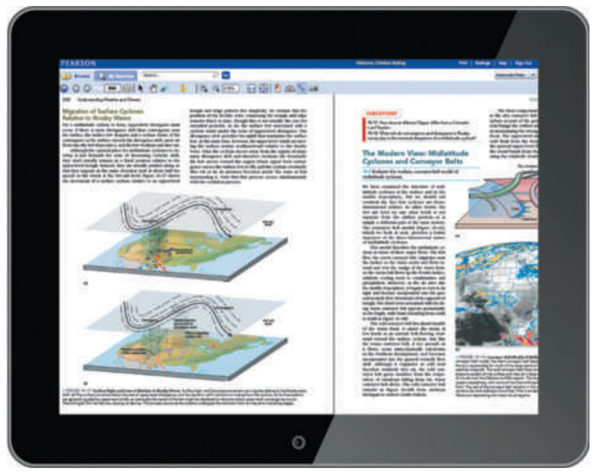

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12–3 FOCUS ON THE ENVIRONMENT AND SOCIETAL IMPACTS

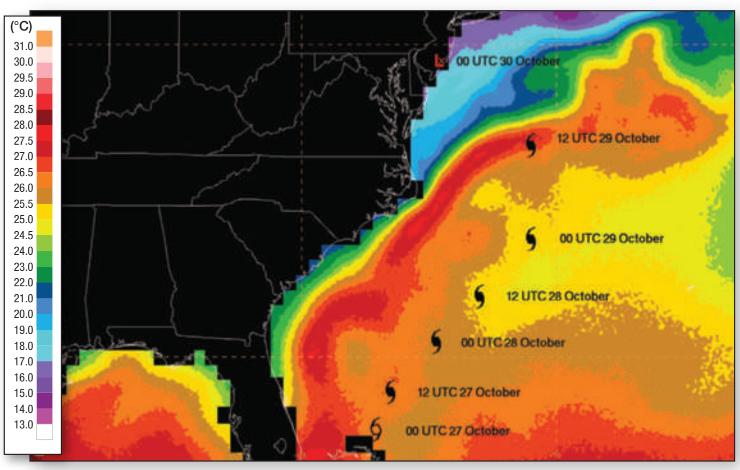
Superstorm Sandy, 2012

In October 2012 Hurricane Sandy—also called Superstorm Sandy—made its mark as one of the most devastating North American weather events in recent years (Figure 12–3–1). First reaching tropical storm status on October 22, it hit Jamaica as a Category 1 hurricane on the 22nd, strengthened further as it migrated northward, and hit eastern Cuba as a Category 3 hurricane on the early morning of October 25.

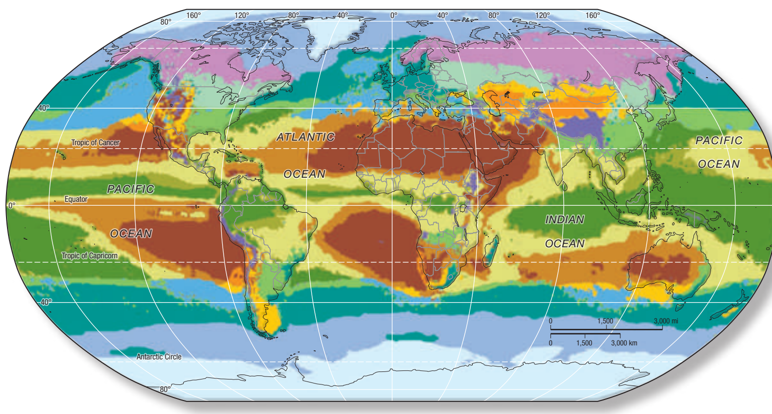
After departing Cuba, Sandy temporarily lost hurricane status, but it reintensified to a hurricane while passing east of southern Florida. The hurricane then continued along a northward track roughly parallel to the U.S. East Coast. On October 29 it hit the mainland south of New York City at Brigantine, New Jersey, with 130 km/hr (81 mph) maximum sustained winds.

▲ FIGURE 12–3–1 **Damage from Superstorm Sandy.** Six months after the storm, the remains of destroyed houses in Mantoloking, New Jersey were still evident.

▲ **FIGURE 15–2 Sea Ice in Antarctica.** Seasonally varying sea ice extent is one of the important factors in the way oceans influence the climate.



SST's (°C) on 28 Oct 2012 with the best track of Sandy plotted at 12 hour intervals

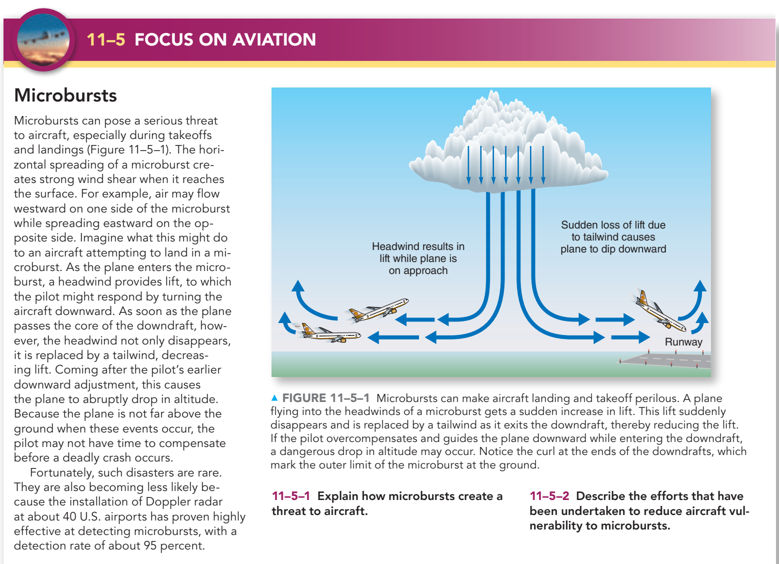


▲ **NEW! *Focus on the Environment and Societal Impacts*** features explore real-world impacts of weather hazards on people and society, illustrating the broad impacts on people and the decision-making that goes into coping with weather events.

▲ **NEW! Coverage of Oceans & Climate** in Chapters 8, 15, and 16 that emphasize how the atmosphere and oceans are interconnected, and how the role of the oceans is key to understanding precipitation patterns, the formation of tropical cyclones, and the impacts of climate change.

the latest science

▼ **UPDATED!** ***Focus on Aviation*** features explore the impacts of various atmospheric phenomena on aviation. Examples include: discussion of winter storms and air travel (Chapter 1); using altimeters to measure altitude (Chapter 4); impacts of icing on aircraft (Chapter 5); recommended pilot responses to icing in different types of clouds (Chapter 6); density altitude and aircraft performance (Chapter 9); lightning and aircraft (Chapter 11); and airport and airline responses to hurricanes (Chapter 12).



11–5 FOCUS ON AVIATION

Microbursts

Microbursts can pose a serious threat to aircraft, especially during takeoffs and landings (Figure 11–5–1). The horizontal spreading of a microburst creates strong wind shear when it reaches the surface. For example, air may flow westward on one side of the microburst while spreading eastward on the opposite side. Imagine what this might do to an aircraft attempting to land in a microburst. As the plane enters the microburst, a headwind provides lift, to which the pilot might respond by turning the aircraft downward. As soon as the plane passes the core of the downdraft, however, the headwind not only disappears, it is replaced by a tailwind, decreasing lift. Coming after the pilot's earlier downward adjustment, this causes the plane to abruptly drop in altitude. Because the plane is not far above the ground when these events occur, the pilot may not have time to compensate before a deadly crash occurs.

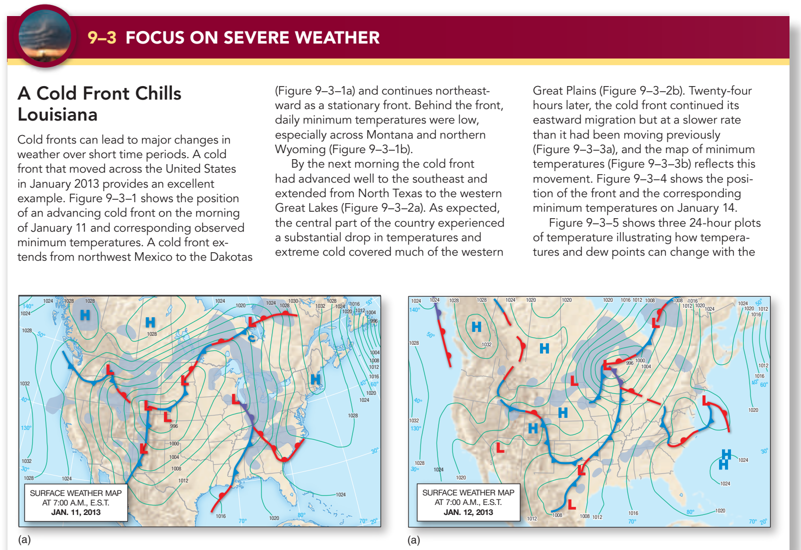
Fortunately, such disasters are rare. They are also becoming less likely because the installation of Doppler radar at about 40 U.S. airports has proven highly effective at detecting microbursts, with a detection rate of about 95 percent.

▲ FIGURE 11–5–1 Microbursts can make aircraft landing and takeoff perilous. A plane flying into the headwinds of a microburst gets a sudden increase in lift. This lift suddenly disappears and is replaced by a tailwind as it exits the downdraft, thereby reducing the lift. If the pilot overcompensates and guides the plane downward while entering the downdraft, a dangerous drop in altitude may occur. Notice the curl at the ends of the downdrafts, which mark the outer limit of the microburst at the ground.

11–5–1 Explain how microbursts create a threat to aircraft.

11–5–2 Describe the efforts that have been undertaken to reduce aircraft vulnerability to microbursts.

▼ **UPDATED!** ***Focus on Severe Weather*** features discuss dramatic and dangerous hazardous weather phenomena, including coverage of many recent events like the deadly 2011 and 2013 tornado seasons and recent deadly cyclones.



9–3 FOCUS ON SEVERE WEATHER

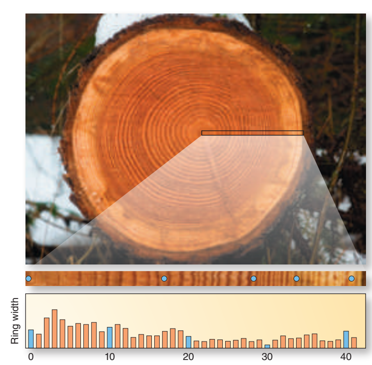
A Cold Front Chills Louisiana

Cold fronts can lead to major changes in weather over short time periods. A cold front that moved across the United States in January 2013 provides an excellent example. Figure 9–3–1 shows the position of an advancing cold front on the morning of January 11 and corresponding observed minimum temperatures. A cold front extends from northwest Mexico to the Dakotas (Figure 9–3–1a) and continues northeastward as a stationary front. Behind the front, daily minimum temperatures were low, especially across Montana and northern Wyoming (Figure 9–3–1b).

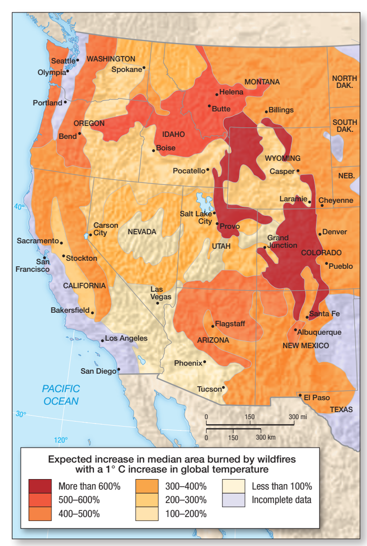
By the next morning the cold front had advanced well to the southeast and extended from North Texas to the western Great Lakes (Figure 9–3–2a). As expected, the central part of the country experienced a substantial drop in temperatures and extreme cold covered much of the western Great Plains (Figure 9–3–2b). Twenty-four hours later, the cold front continued its eastward migration but at a slower rate than it had been moving previously (Figure 9–3–3a), and the map of minimum temperatures (Figure 9–3–3b) reflects this movement. Figure 9–3–4 shows the position of the front and the corresponding minimum temperatures on January 14.

Figure 9–3–5 shows three 24-hour plots of temperature illustrating how temperatures and dew points can change with the

▶ **UPDATED!** Coverage of **climate change** impacts and projections integrated throughout, including the latest findings of the IPCC's 5th Assessment Report.



▲ FIGURE 16–5 **Evidence from Tree Rings.** The blue dots on the middle panel correspond to each tenth-year.



▲ FIGURE 16–26 **Projected Changes in Wildfires.** The map shows the expected percentage increase in median area burned by wildfires with a 1 °C increase in global temperature.

principles & tools of **meteorology**

11–4 FORECASTING

Doppler Radar

Just as we are able to distinguish different colors of light by their wavelengths, so can we differentiate sounds by the length of their sound waves. If an object making a sound is moving away from a listener, the sound waves are stretched out and assume a lower pitch. Sound waves are compressed when an object moves toward the listener, making them higher pitched. Unconsciously, we use this principle, called the **Doppler effect**, to determine whether an ambulance siren is coming closer or moving away. If the pitch of the siren seems to become higher, we know the ambulance is getting nearer (of course, the siren would also sound louder). A similar process occurs when electromagnetic waves are reflected by a moving object: The light shifts to shorter wavelengths when reflected by an object moving toward the receiver and to longer wavelengths as it bounces off an object moving away from the receiver.

Applying the Doppler Effect

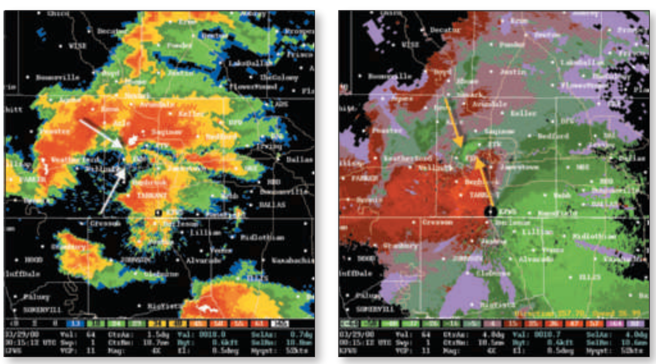
Doppler radar is a type of radar system that takes advantage of this principle. It allows the user to observe the movement of raindrops and ice particles (and thus determine wind speed and direction) from the shift in wavelength of the radar waves, as well as the intensity of precipitation. Like any other type of radar, Doppler radar has a transmitter that emits pulses of electromagnetic energy with wavelengths on the order of several centimeters. Depending on the wavelength used, water droplets and snow crystals above certain critical sizes reflect a portion of the radar's electromagnetic energy back to the transmitter/receiver. In the case of particularly violent tornadoes that pick up large objects from the ground, the radar will observe this airborne material and display it as a *debris ball*.

Doppler radar is special in its ability to observe the motion of the cloud constituents. If a cloud droplet is moving away from the radar unit, the wavelength of the beam is slightly elongated as it bounces off the reflector. Such reflections are normally indicated on the display monitor as reddish to yellow. Likewise, a droplet moving toward the radar unit undergoes a shortening of the wavelength. Echoes from these constituents are displayed as blue or green on the radar screen.

Radar Scans

A radar unit must rotate 360 degrees to get a complete picture of the weather situation surrounding the transmitter/receiver unit. When the transmitter makes one complete rotation at a fixed angle, it is said to have completed a **sweep**. The angle can then be increased as a second sweep is taken that depicts a higher cloud level. This can be repeated several times so that the radar can peer into multiple levels of the cloud. The compilation of all the individual sweeps takes approximately 5 to 10 minutes and produces a **volume sweep**.

Figure 11–4–1 shows a pair of Doppler radar images of a major storm near Dallas–Fort Worth, Texas, on March 29, 2000. Figure 11–4–1a shows the reflectivity of the storm, with redder regions indicating intense precipitation and green areas representing less intense precipitation. The white arrows point toward a hook echo (described in the main text of this chapter). Figure 11–4–1b displays the *storm radial velocity (SRV) pattern*, which describes the motions taking place within the cloud. SRV displays use redder colors to represent winds blowing away



(a) (b)

Video Identifying Tornadic Thunderstorms Using Radar Velocity Data

http://goo.gl/szdHJQ

▲ FIGURE 11–4–1 **Doppler Radar Images.** A storm near Dallas–Fort Worth, Texas, on March 29, 2000. Part (a) depicts the intensity of precipitation; part (b) shows the storm radial velocity (SRV) pattern, which is the movement of different parts of the storm toward or away from the radar unit.

10–3 PHYSICAL PRINCIPLES

A Closer Look at Divergence and Convergence

Upper-level divergence and convergence are changes in the horizontal area occupied by an air parcel and result from changes in vorticity as air flows. This relationship between divergence and vorticity can be summarized in the simple equation

$$-\frac{1}{\zeta}\frac{\Delta\zeta}{\Delta t} = div \quad \text{vorticity and divergence}$$

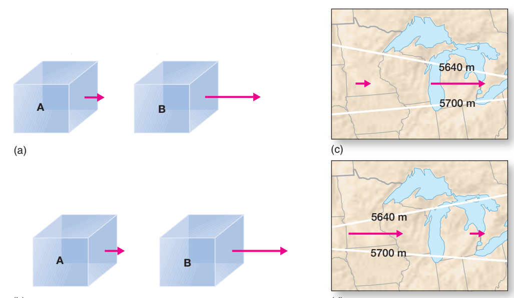
where $-\frac{1}{\zeta}\frac{\Delta\zeta}{\Delta t}$ is the standardized change (here, the decrease) in absolute vorticity (ξ) with respect to time (t), and div = divergence. If absolute vorticity increases, convergence must result. If absolute vorticity decreases, divergence must result.

Divergence and convergence can occur in two ways. The first is by an increase or a decrease in the speed of air as it flows. The second is by a stretching out or pinching inward of the air, in a direction perpendicular to the direction in which it is moving. The divergence and convergence described earlier in this chapter can take either form.

Speed Divergence and Speed Convergence

Speed divergence and **speed convergence** occur when air moving in a constant direction either speeds up or slows down. Consider the two parcels of air, *A* and *B*, in Figure 10–3–1a. Both parcels are moving in the same direction, but parcel *B* moves faster, as indicated by the length of the arrows. Because the leading parcel has greater speed than the one behind it, the distance between the two increases with time Figure 10–3–1b. This is an example of speed divergence.

This form of divergence is analogous to what might happen in a race with many entrants at the starting line. Initially, the runners cluster together, with little space between them. When the starting gun goes off, the people at the front of the



(a) (b) (c) (d)

▲ FIGURE 10–3–1 **Speed Divergence and Convergence.** (a) Two hypothetical parcels of air are moving in the same direction, with the one in front moving faster. (b) At some interval of time later, the leading parcel has moved even farther ahead, creating speed divergence. This is also illustrated in (c), with the tighter spacing of height contours to the east creating speed divergence. Speed convergence is occurring in (d). Note that the values shown on the lines in (c) and (d) represent the height of the 500 mb level in meters.

▲ UPDATED! *Forecasting*

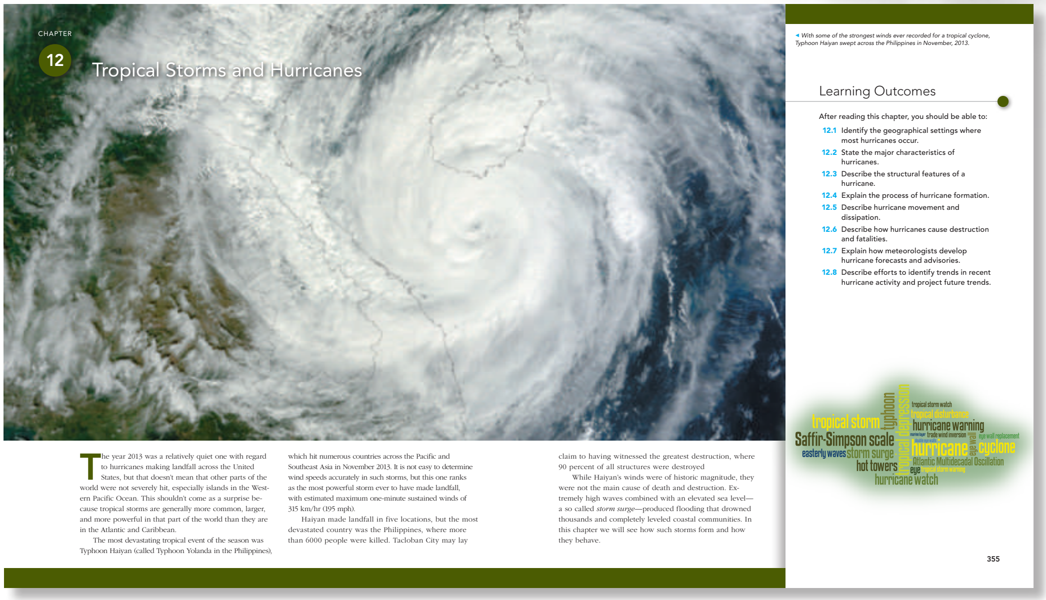
features apply the topics of the chapter to forecasting principles and often include simple "rules of thumb" that help students make their own forecasts. This text contains numerous examples of how physical principles are employed in weather forecasting.

▲ UPDATED! Physical Principles

complement the main narrative by delving deeper into qualitative topics. More mathematical in nature than the rest of the text, these boxes accommodate students who have a more quantitative interest in the topic.

structured learning

Understanding Weather and Climate provides an active structured learning path to help guide students towards mastery of key meteorological concepts.



CHAPTER 12 Tropical Storms and Hurricanes

◂ *With some of the strongest winds ever recorded for a tropical cyclone, Typhoon Haiyan swept across the Philippines in November, 2013.*

Learning Outcomes

After reading this chapter, you should be able to:

12.1 Identify the geographical settings where most hurricanes occur.
12.2 State the major characteristics of hurricanes.
12.3 Describe the structural features of a hurricane.
12.4 Explain the process of hurricane formation.
12.5 Describe hurricane movement and dissipation.
12.6 Describe how hurricanes cause destruction and fatalities.
12.7 Explain how meteorologists develop hurricane forecasts and advisories.
12.8 Describe efforts to identify trends in recent hurricane activity and project future trends.

The year 2013 was a relatively quiet one with regard to hurricanes making landfall across the United States, but that doesn't mean that other parts of the world were not severely hit, especially islands in the Western Pacific Ocean. This shouldn't come as a surprise because tropical storms are generally more common, larger, and more powerful in that part of the world than they are in the Atlantic and Caribbean.

The most devastating tropical event of the season was Typhoon Haiyan (called Typhoon Yolanda in the Philippines), which hit numerous countries across the Pacific and Southeast Asia in November 2013. It is not easy to determine wind speeds accurately in such storms, but this one ranks as the most powerful storm ever to have made landfall, with estimated maximum one-minute sustained winds of 315 km/hr (195 mph).

Haiyan made landfall in five locations, but the most devastated country was the Philippines, where more than 6000 people were killed. Tacloban City may lay claim to having witnessed the greatest destruction, where 90 percent of all structures were destroyed

While Haiyan's winds were of historic magnitude, they were not the main cause of death and destruction. Extremely high waves combined with an elevated sea level—a so called *storm surge*—produced flooding that drowned thousands and completely leveled coastal communities. In this chapter we will see how such storms form and how they behave.

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◂ UPDATED! ***Learning Outcomes*** listed at the beginning of the chapter and now integrated within chapter sections help students prioritize key concepts and skills.

◂ NEW! ***Word Clouds*** at the start of each chapter emphasize the key topics and concepts of the chapter.

Visual Analysis

This satellite image shows a large, powerful storm over the North Atlantic Ocean on March 26, 2014.

4.1. The wispy faint clouds blowing from west to east in the top part of the image are far above the friction layer. Assuming gradient flow, draw lines showing the orientation of height contours.

4.2. At lower levels do clouds appear to spiral into or out of the storm's center? Is this a cyclone or anticyclone?

▴ **Superstorm of March 2014.** After crossing the continental U.S., the storm intensified over the Atlantic Ocean.

CHECKPOINT

15.1 What is climate?

15.2 What considerations enter the decision regarding the length of period to use in a climatic average?

15.3 What are some of the factors that determine the climate of a location?

15.4 What are some of the problems encountered when trying to divide the Earth into climatic zones?

▴ UPDATED! ***Checkpoint Questions*** are integrated throughout the chapters after major sections, giving students a chance to stop, practice, and apply their understanding of key chapter content.

▴ NEW! ***Visual Analysis Activities*** at the end of chapters draw on visualizations of real-world meteorology phenomena and data, asking students to make observations and predictions, and to demonstrate critical thinking, image interpretation, and data analysis skills.

continuous learning

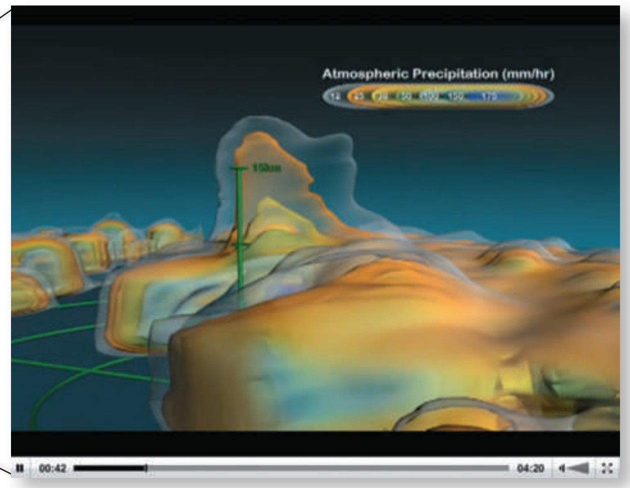
BEFORE CLASS

Mobile Media & Reading Assignments Ensure Students Come to Class Prepared

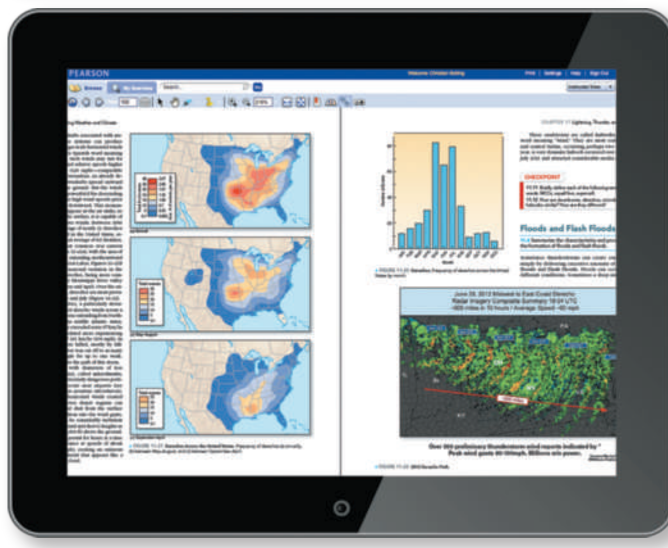
▼ **NEW!** ***Mobile-Enabled Quick Response (QR)*** codes integrated throughout each chapter empower students to use their mobile devices to learn as they read, providing instant access to over 120 Videos and Animations of real-world atmospheric phenomena and visualizations of key physical processes. All media can be assigned with quizzes in MasteringMeteorology.

Video
Hot Towers and Hurricane Intensification

http://goo.gl/jJmpo



► **Pearson eText** in MasteringMeteorology gives students access to *Understanding Weather and Climate, 7th Edition* whenever and wherever they can access the Internet. The eText includes powerful interactive and customization functions. Users can create notes, highlight text in different colors, create bookmarks, zoom, and click hyperlinked words and phrases to view definitions. Pearson eText also links students to rich media, enabling them to view videos and animations as they read the text, and offers a full-text search and the ability to save and export notes. Students can use the free Pearson eText app to access the eText on iPad and Android tablet devices.



Pre-Lecture Reading Quizzes are easy to customize and assign.

NEW! ***Reading Quiz Questions*** in MasteringMeteorology ensure that students complete the assigned reading before class and stay on track with reading assignments. Reading Questions are 100% mobile ready and can be completed by students on their mobile devices.

before, during, & after class

DURING CLASS
Learning Catalytics

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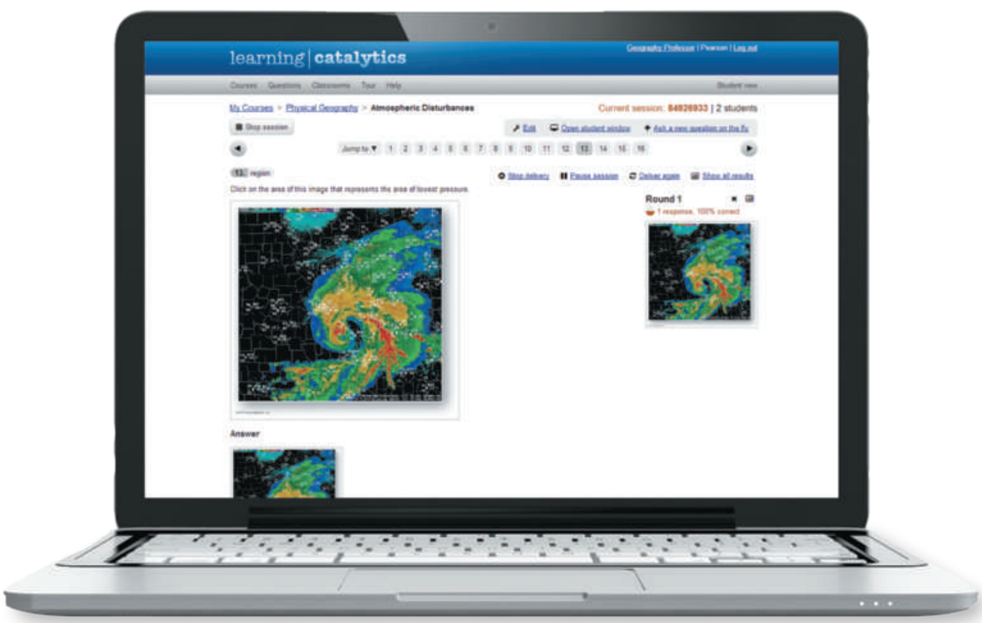
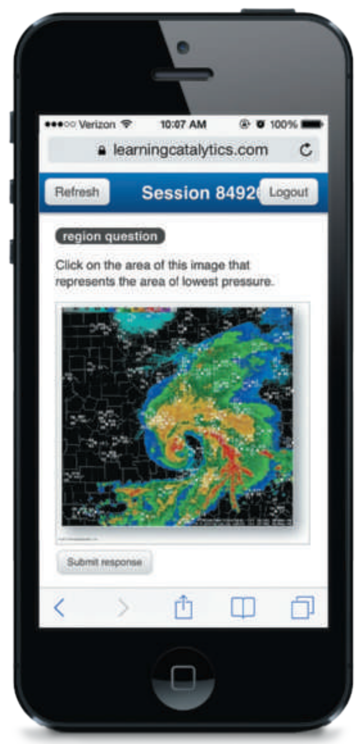
What has Teachers and Students excited? Learning Catalytics, a 'bring your own device' student engagement, assessment, and classroom intelligence system, allows students to use their smartphone, tablet, or laptop to respond to questions in class. With Learning Catalytics, teachers can:

- Assess students in real-time using open ended question formats to uncover student misconceptions and adjust lecture accordingly.
- Automatically create groups for peer instruction based on student response patterns, to optimize discussion productivity.





Enrich Lecture with Dynamic Media

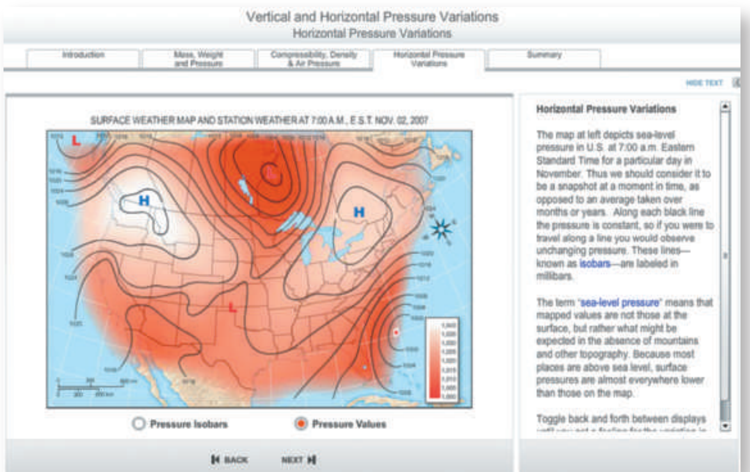
Teachers can incorporate dynamic media into lecture, such as Geoscience Animations, Videos, and MapMaster Interactive Maps.

MasteringMeteorology

AFTER CLASS

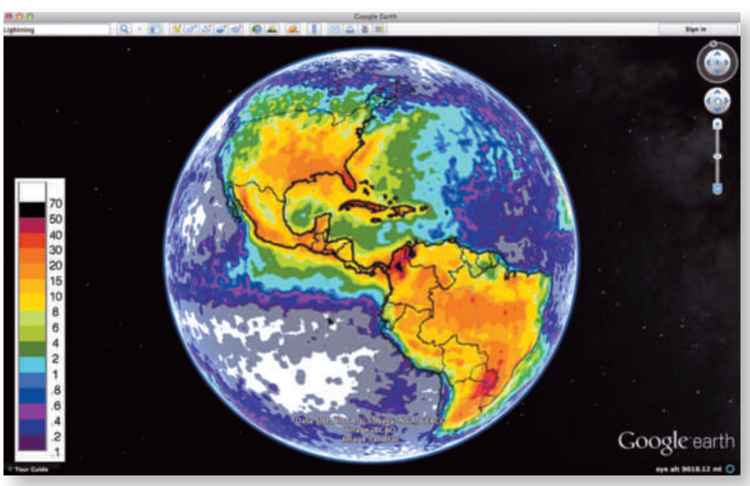
Easy-to-Assign, Customizable, Media-Rich, and Automatically-Graded Assignments

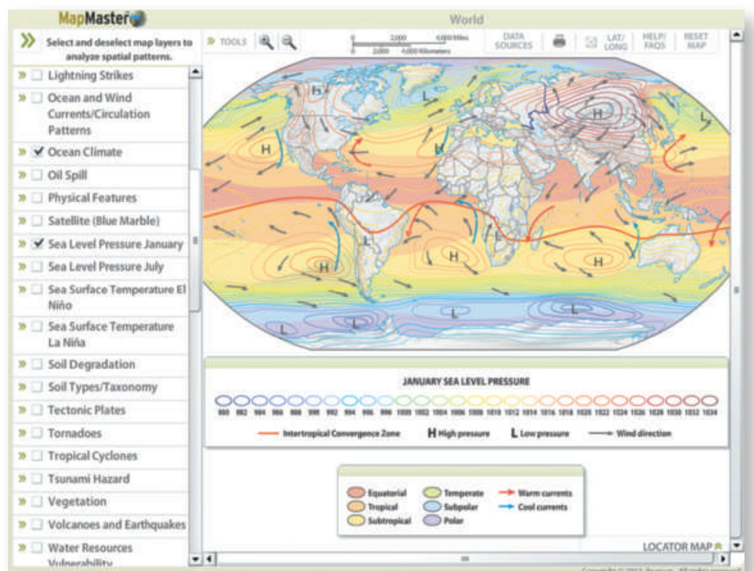
The breadth and depth of media content available in MasteringMeteorology is unparalleled, allowing teachers to quickly and easily assign homework to reinforce key concepts. Most media activities are supported by automatically-graded multiple choice quizzes with hints and specific wrong answer feedback that helps coach students towards mastery of the concepts.



◄ **Interactive Tutorials** cover basic principles of atmospheric science, with three-dimensional diagrams and animations. The media modules follow a tutorial style, with explanations and new vocabulary introduced incrementally.

▼ **Encounter Activities** provide rich, interactive Google Earth explorations of meteorology concepts to visualize and explore Earth's physical landscape and atmospheric processes.





▲ **MapMaster Interactive Map Activities** are inspired by GIS, allowing students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. This tool includes zoom and annotation functionality, with hundreds of map layers leveraging recent data from sources such as NOAA, NASA, USGS, United Nations, and the CIA.

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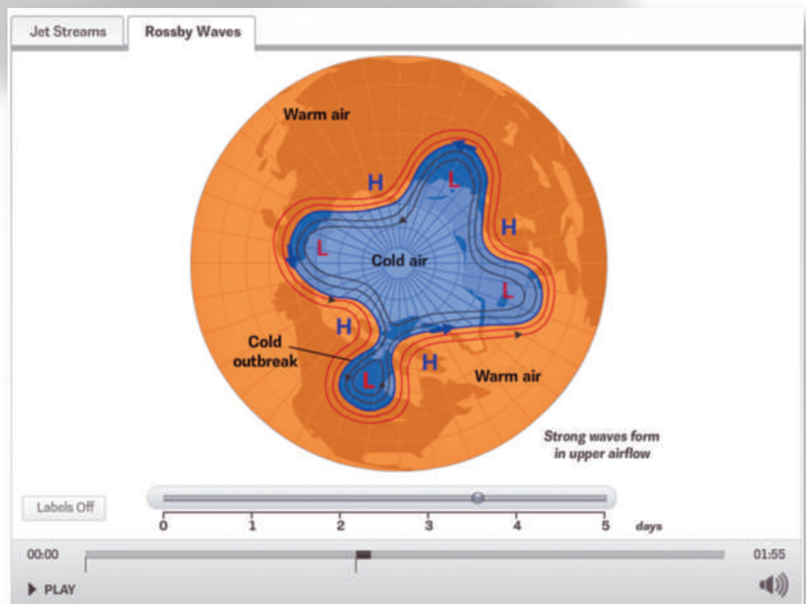
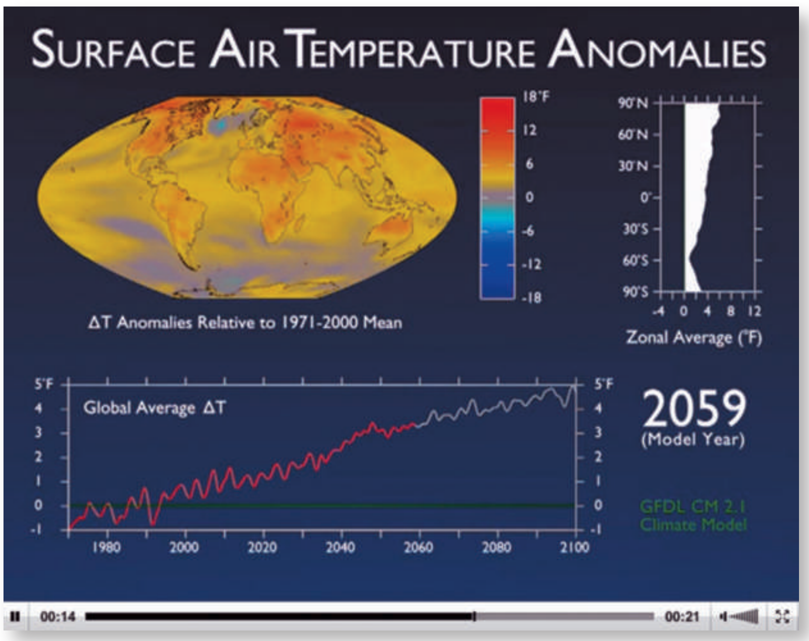
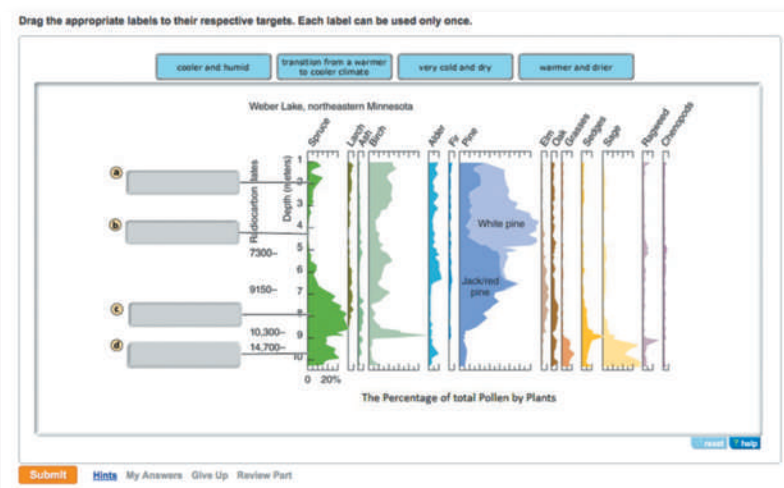
▶ **Geoscience Animations** help students visualize the most challenging physical processes in the physical geosciences with schematic animations that include audio narration.

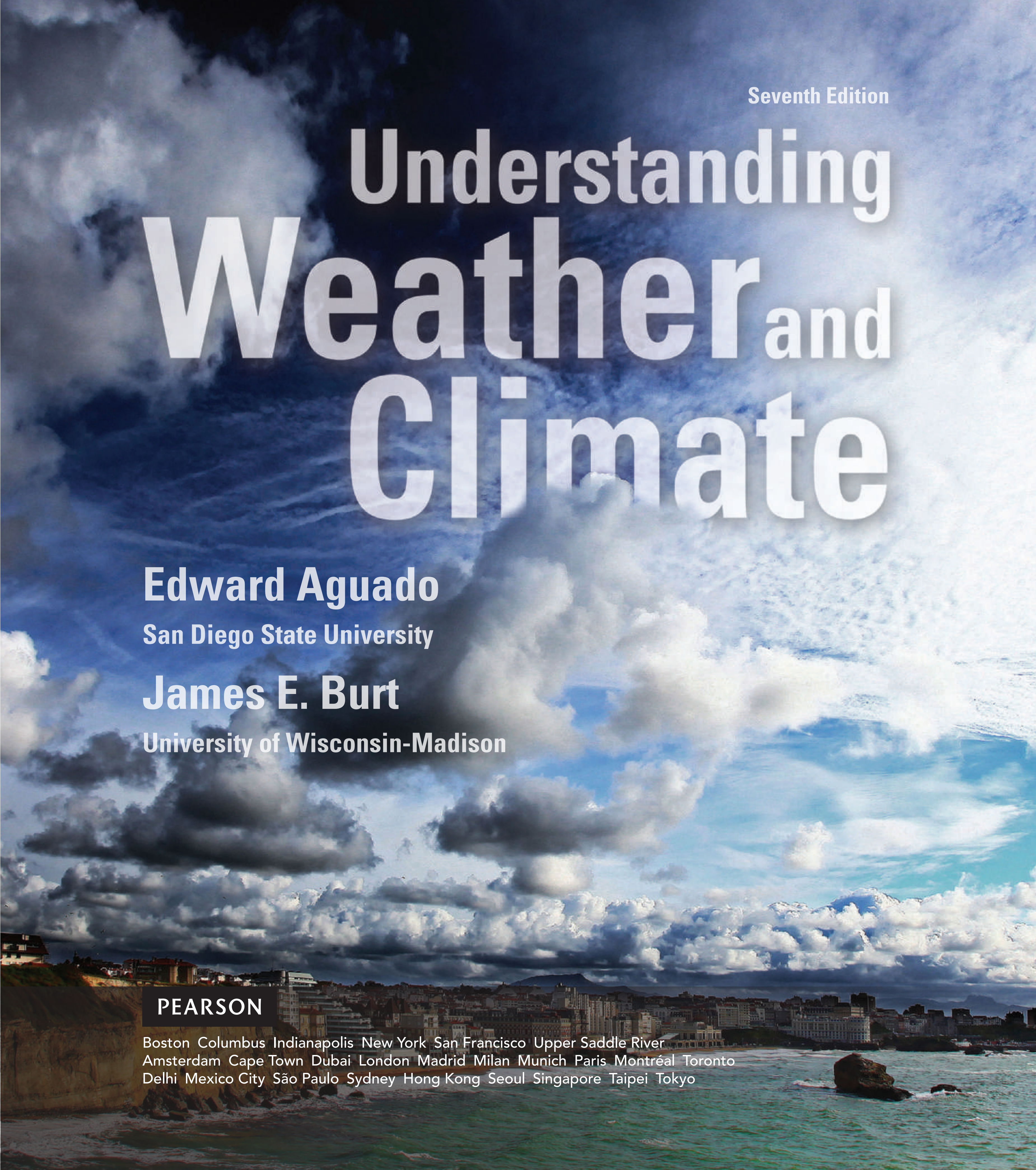




◀ **Videos** provide students with real-world case studies of atmospheric phenomena and engaging visualizations of critical data.

▶ **GeoTutor Coaching Activities** help students master the toughest physical geoscience concepts with highly visual, kinesthetic activities focused on critical thinking and application of core geoscience concepts.





Seventh Edition

Understanding Weather and Climate

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University of Wisconsin-Madison

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Brief Contents

about our sustainability initiatives

Pearson recognizes the environmental challenges facing this planet and also acknowledges our responsibility in making a difference. This book is carefully crafted to minimize environmental impact. The binding, cover, and paper come from facilities that minimize waste, energy consumption, and the use of harmful chemicals. Pearson closes the loop by recycling every out-of-date text returned to our warehouse.

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PEARSON

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Preface

The atmosphere is the most dynamic of all Earth's spheres. In no other realm do events routinely unfold so quickly, with so great a potential impact on humans. Some of the most striking atmospheric disturbances (such as tornadoes) can take place over time scales on the order of minutes—but nevertheless have permanent consequences. Events such as the California drought, which began in 2011 and showed no signs of abatement by mid-2014, take longer, but can have much more widespread effects. Water levels have dropped precipitously in reservoirs, the state's huge agricultural industry has been severely impacted, water allocations have been reduced, and many areas have been threatened by unusually dangerous wildfires. While catastrophes such as this are momentous, even the most mundane of atmospheric phenomena influence our lives on a daily basis (for instance, the beauty of blue skies or red sunsets, rain, or the daily cycle of temperature).

Atmospheric processes, despite their immediacy on a personal level and their importance in human affairs on a larger level, are not readily understood by most people. This is probably not surprising, given that the atmosphere consists primarily of invisible gases, along with suspended, frequently microscopic particles, water droplets, and ice crystals.

Understanding Weather and Climate is a college-level text intended for both science majors and nonmajors taking their first course in atmospheric science. We have attempted to write a text that is informative, timely, engaging to students, and easily used by professors. In this book, our overriding goal is to bridge the gap between abstract explanatory processes and the expression of those processes in everyday events. We have written the book so that students with little or no science background will be able to build a nonmathematical understanding of the atmosphere.

That said, we do not propose to abandon the foundations of physical science. We know from our own teaching experience that physical laws and principles can be mastered by students of widely varying backgrounds. In addition, we believe one of meteorology's great advantages is that reasoning from fundamental principles explains so much of the field. Compared to some other disciplines, this is one in which there is an enormous payoff for mastering a relatively small number of basic ideas.

Finally, our experience is that students are always excited to learn the "why" of things, and to do so gives real meaning to "what" and "where." For us, therefore, the idea of forsaking explanation in favor of a purely descriptive approach has no appeal whatsoever. Rather, we propose merely to replace mathematical proof (corroboration by formal argument) with qualitative reasoning and appeal to everyday occurrences. As the title implies, the goal remains understanding atmospheric behavior.

New to the Seventh Edition

- **NEW MasteringMeteorology** helps teachers maximize class time with customizable, easy-to-assign, and automatically graded assessments that motivate students to learn outside of class and arrive prepared for lecture. MasteringMeteorology offers assignable activities that include Interactive Tutorials, GIS-inspired MapMaster™ interactive maps, Encounter Google Earth Explorations, videos, Geoscience Animations, Map Projection Tutorials, GeoTutor coaching activities on the toughest topics in the geosciences, Dynamic Study Modules that provide each student with a customized learning experience, end-of-chapter questions and exercises, reading quizzes, Test Bank questions, a Pearson eText version of the book, and more.
- **NEW Quick Response (QR) codes** integrated throughout each chapter empower students to use their mobile devices for learning as they read, providing instant access to over 120 videos and animations of real-world atmospheric phenomena and visualizations of key physical processes.
- **NEW *Focus on the Environment and Societal Impacts*** features explore the impact of weather hazards on people and society, not just by looking at the physical principles, but also by looking at the broader human issues, as well as mitigation policies and strategies. These case studies are grounded in real-world examples that illustrate the broad effects of weather on people and society and the decision making that goes into coping with weather events.
- **NEW Emphasis on oceans and their role in regulating weather and climate**, including unique dedicated sections on oceans and our climate in Chapters 8, 15, and 16. These sections emphasize how the atmosphere and oceans are interconnected parts of the larger Earth system, and how the role of the oceans is key to understanding such important phenomena as precipitation patterns, the formation of tropical cyclones, and the impacts of climate change.
- **NEW and UPDATED *Focus on Aviation*** features explore the meteorological impacts of weather on aviation. New topics include *Using Altimeters to Monitor Altitude* (Chapter 4), *Density Altitude and Aircraft Performance* (Chapter 9), and *Airports' and Airlines' Response to Hurricanes* (Chapter 12).
- **UPDATED coverage of climate change** integrated throughout, including the findings of the IPCC's Fifth Assessment Report.
- **NEW *Word Clouds*** presented at the start of each chapter emphasize the key topics and concepts of the chapter.

- **NEW *Visual Analysis Activities*** at the end of each chapter draw on visualizations of real-world meteorology phenomena and data, asking students to make observations and predictions and to demonstrate higher-level critical thinking and data analysis skills. These activities are also available in MasteringMeteorology.
- **NEW Equations** are highlighted and defined throughout the text for easy reference.
- **NEW** sections and features on the **scientific method** and its role in atmospheric science (Chapter 1), the Coriolis force (Chapter 4), and maintaining the general circulation (Chapter 8).
- **NEW full-color reference globes and maps** inside the front and back covers provide students with dynamic satellite and cartographic reference imagery.
- The **latest data, case studies, applications,** and current **examples from meteorology today** are integrated to make the seventh edition the most current and relevant introduction to meteorology. For example, Chapter 3 includes the most up-to-date values of the global energy balance; Chapter 8 discusses El Niño types and their differing effects on U.S. temperatures; Chapter 10 offers a scientifically current description of midlatitude cyclones against the background of the original polar front theory; Chapter 11 presents the most recent instructions on tornado safety that reflect outcomes from the deadly tornado outbreaks of 2013 and new material on floods and flash floods; and Chapter 12 presents updated statistics on hurricane incidence. Chapter 13 focuses on the extreme winter of 2013 to illustrate the methods and pitfalls of short and long-term forecasting. Chapter 15 has new maps of global climates based on state-of-the art ocean and land data sets. Chapter 16 has new material on climate change, including synopses of the Fifth IPCC Assessment report and the 2014 Third National Climate Assessment (NCA).

Distinguishing Features

Scientific Literacy and Currency We emphasize scientific literacy throughout the book. This emphasis gives students an opportunity to develop a deeper understanding about the building blocks of atmospheric science and serves as tacit instruction regarding the workings of all the sciences. For instance, in Chapter 2 we cover the molecular changes that occur when radiation is absorbed or emitted, items that are often considered a "given" in introductory texts. In Chapter 3 these basic ideas are used to help build student understanding of why individual gases radiate and absorb particular wavelengths of radiation and to illustrate how processes operating at a subatomic level can manifest themselves at global scales. Similarly, our discussion of anthropogenic warming in Chapter 16 includes cloud, water vapor, and lapse rate feedbacks in order to provide a more complete account of the uncertainties surrounding this critical environmental topic.

An emphasis on scientific literacy is effectively implemented only if it is accompanied by careful attention to currency. We believe that two kinds of currency are required in a text: an integration of current *events* as they relate to the topic at hand, and an integration of current *scientific thinking*. For instance, the reader will find discussion of both recent hurricane activity and the most recent theories regarding the mechanisms that generate severe storms. Scientific literacy also calls for attention to language—after all, precision of language is an important distinguishing characteristic of science, one that sets it apart from other intellectual activities.

Instructor Flexibility During the writing process, we have enjoyed interacting with many of our colleagues who teach courses in weather and climate on a regular basis. It was especially interesting to see how little consensus exists regarding topic order (truth be told, the authors of this book don't agree on the optimal sequence). With this in mind, we tried to minimize the degree to which individual chapters depend on material presented earlier. Thus, instructors who prefer a chapter order different from the one we ultimately chose will not be disadvantaged.

Emphasis on Climate Change In 2013 and 2014, the Intergovernmental Panel on Climate Change (IPCC) released its latest report on the current knowledge of climate change and human impacts. The seventh edition of *Understanding Weather and Climate* makes heavy reference to that work, and has updated climate statistics through 2014, and post-IPCC developments are included throughout. These sections present physically based explanations behind the changes that have occurred and are likely to occur in the future.

Emphasis on Forecasting In addition to a comprehensive chapter on the topic, this text contains numerous examples of how physical principles are employed in weather forecasting. We have included several discussions of the use of thermodynamic diagrams in weather forecasting and analysis. These charts are extremely valuable but not immediately comprehensible to most students. To alleviate this problem, we introduce thermodynamic diagrams in a sequential fashion. That is, their use for plotting vertical temperature profiles is presented in the chapter on temperature. We expand on this in the chapter on atmospheric moisture to show how various measures of humidity can also be determined with the aid of the charts. Thus, instructors can teach their students how to use these diagrams without inundating them with excessive detail all at once.

Current Applications of Meteorology This edition presents a greater number of weather maps and images to illustrate how atmospheric phenomena occur in everyday settings. The new examples have been selected for currency and illustrative value. Special attention has been given to some of the most notable hurricanes and typhoons of recent years, along with 2013 tornado outbreaks, and the brutal winter of 2013–2014 in eastern North America.

Readability In contrast to the more formal scientific style used in many science textbooks, we have chosen to adopt more casual prose. Our goal is to present the material in language that is clear, readable, and friendly to the student reader. We employ frequent headings and subheadings to help students follow discussions and identify the most important ideas in each chapter. As a rule, we keep technical language to a minimum.

Dynamic Media

A fundamental feature of this book is the integration of the classic print textbook model with instructional technology. These dynamic media resources are delivered through the new **www.MasteringMeteorology.com** platform, with many online videos and animations available for students to access directly from the print textbook pages with QR codes that can be scanned with mobile devices. The online media consist of several components.

Interactive Tutorials These 17 software modules cover the basic principles of atmospheric science and have been used successfully by thousands of students. They rely heavily on three-dimensional diagrams and animations to present material not easily visualized using conventional media. The software modules follow a tutorial style, with explanations and new vocabulary introduced incrementally, building on what was presented earlier in the modules and what was presented in the text. The tutorials are best used in conjunction with the assigned readings. In choosing topics for the modules, we have emphasized material that is both difficult to master and has the potential to benefit from digital technology. We advise that you first view a tutorial in its entirety. If additional review is needed, you can easily move within a tutorial to the section under discussion.

Videos In addition to the tutorials, the seventh edition contains more than 100 video clips that depict events and phenomena discussed in the text. Many new movies have been added to the seventh edition. Example topics include waterspouts, seasonal changes in snow cover, the making of a superstorm, three-dimensional simulations of thunderstorm development, and the ocean's green machines. Teachers can assign video quizzes to students within MasteringMeteorology.

Interactive Maps GIS-inspired MapMaster™ interactive maps allow students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. The interactive maps allows users to zoom and annotate the maps, with hundreds of map layers and thousands of sublayers from sources such as NOAA, NASA, USGS, the United Nations, the U.S. Census Bureau, the CIA, the World Bank, and the Population Reference Bureau. Icons in the print book indicate when an associated map exists in MapMaster. Teachers can assign customizable interactive map activities in MasteringMeteorology.

Focus on Learning

The chapters offer a number of study aids:

- *Learning Outcomes* are outlined at the beginning of each chapter and within chapter sections, helping students prioritize key concepts and skills.
- *Checkpoint Questions* are integrated throughout the chapters after major sections, giving students a chance to stop, practice, and apply their understanding of key chapter content.
- *Did You Know* features highlight interesting meteorological facts in every chapter.
- *Focus on the Environment and Societal Impacts* features highlight environmental and human impact issues as they relate to the study of the atmosphere.
- *Focus on Severe Weather* features focus on dramatic and dangerous severe and hazardous weather phenomena, including coverage of many recent events like the deadly 2011 and 2013 tornado seasons.
- *Focus on Aviation* features explore the impacts of various atmospheric phenomena on aviation. Examples include discussion of winter storms and air travel (Chapter 1), impacts of icing on aircraft (Chapter 5), recommended pilot responses to icing in different types of clouds (Chapter 6), and lightning and aircraft (Chapter 11).
- *Physical Principles* features are more mathematical in nature and accommodate students who have a more quantitative interest in the topic.
- *Forecasting* features apply the principles discussed in the chapter to forecasting and often include simple "rules of thumb" that help students make their own forecasts.
- *Summary.* Each chapter concludes with a chapter summary highlighting the main points in the chapter.
- *Review Questions.* These Review Questions test reading comprehension and can be answered from information presented in the chapter.
- *Critical Thinking.* These questions require students to use material presented in the chapter to work out answers relevant to real-world questions.
- *Problems & Exercises* encourage students to work out solutions to numerical questions to gain a better understanding of chapter material.
- *Quantitative Problems.* The MasteringMeteorology website features quantitative exercises to accompany each chapter.
- *Visual Analysis Activities.* These activities ask students to make observations and predictions and to demonstrate higher-level critical thinking and data analysis skills.
- *Key Terms* are printed in boldface when first introduced. Most are also listed at the end of each chapter, along with the page number on which each first appears. All key terms are defined in the glossary at the end of the book, and interactive glossary and flashcard versions of key terms are available in MasteringMeteorology.

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MasteringMeteorology™ with Pearson eText. The Mastering platform is the most widely used and effective online homework, tutorial, and assessment system for the sciences. It delivers self-paced tutorials that provide individualized coaching, focus on course objectives, and are responsive to each student's progress. The Mastering system helps teachers maximize class time with customizable, easy-to-assign, and automatically graded assessments that motivate students to learn outside of class and arrive prepared for lecture. MasteringMeteorology offers:

- Assignable activities that include Interactive Tutorials, GIS-inspired MapMaster™ interactive maps, Encounter Google Earth Explorations, Videos, Geoscience Animations, Map Projection Tutorials, GeoTutor coaching activities on the toughest topics in the geosciences, Dynamic Study Modules that provide each student with a customized learning experience, end-of-chapter questions and exercises, reading quizzes, Test Bank questions, and more.
- A student Study Area with GIS-inspired MapMaster™ interactive maps, Videos, Geoscience Animations, web links, glossary flashcards, "In the News" RSS feeds, chapter quizzes, PDF downloads of outline maps, an optional Pearson eText including versions for iPad and Android devices, and more.

Pearson eText gives students access to the text whenever and wherever they can access the Internet. The eText pages look exactly like the printed text and include powerful interactive and customization functions, including links to the multimedia. Students who have registered for MasteringMeteorology can download the free Pearson eText app to access the eText on iPad and Android tablets.

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. This manual is designed to complement any introductory meteorology or weather and climate course.
- ***Goode's World Atlas,* 23rd edition [0133864642]** *Goode's World Atlas* has been the world's premiere educational atlas since 1923—and for good reason. It features more than 250 pages of maps, from definitive physical and political maps to important thematic maps that illustrate the spatial aspects of many important topics. Topics include: global climate change, sea-level rise, CO_2 emissions, polar ice fluctuations, deforestation, extreme weather events, infectious diseases, water resources, and energy production.
- ***Dire Predictions: Understanding Climate Change,* 2nd edition by Mike Mann and Lee Kump [0133909778]** In just over 200 pages, this practical text presents and expands on the essential findings of the Intergovernmental Panel on Climate Change (IPCC) 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.
- ***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 MasteringMeteorology, 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, online quizzes whose results can be e-mailed to teachers, and a corresponding Google Earth KMZ file.
  - ***Geoscience Animation Library on DVD,* 5th Edition [0321716841] Geoscience Animations** illuminate the most difficult-to-visualize topics from across the physical geosciences, such as solar system formation, hydrologic cycle, plate tectonics, glacial advance and retreat, and global warming. Animations include audio narration and text transcript, with assignable multiple-choice quizzes to select animations in MasteringMeteorology to help students master these core physical process concepts.
  - ***Earth Report* Geography Videos on DVD [0321662989]** This three-DVD set is designed to help students visualize how human decisions and behavior have affected the environment and how individuals are taking steps toward recovery. With topics ranging from poor land management promoting the devastation of river systems in Central America to the struggles for electricity in China and Africa, these 13 videos from Television for the Environment's global *Earth Report* series recognize the efforts of individuals around the world to unite and protect the planet. Teachers can assign video clips with assessment in MasteringMeteorology.

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- ***Instructor Resource Manual* (download only) by Doug Gamble, University of North Carolina, Wilmington [0321993659]** The *Instructor Resource Manual* is intended as a resource for both new and experienced instructors. It includes a variety of lecture outlines, additional source materials, teaching tips, advice about how to integrate visual supplements (including the Web-based resources), and various other ideas for the classroom. See **www.pearsonhighered.com/irc**.
- **TestGen® Computerized *Test Bank* (download only) by Jonathan D. W. Kahl, University of Wisconsin–Milwaukee [0321992539]** TestGen® is a computerized test generator that lets instructors view and edit *Test Bank* questions, transfer questions to tests, and print tests in a variety of customized formats. This *Test Bank* includes more than 2000 multiple-choice, fill-in-the-blank, and short-answer/essay questions. Questions are correlated to the text's Learning Outcomes, Pearson's Global Science Outcomes, the section of each chapter, the revised U.S. National Geography Standards, and Bloom's taxonomy to help instructors better map the assessments against both broad and specific teaching and learning objectives. The *Test Bank* is also available in Microsoft Word and is importable into systems such as Blackboard. See **www.pearsonhighered.com/irc**.
- ***Instructor Resource DVD* [0321993667]** The Instructor Resource DVD provides a collection of resources to help teachers make efficient and effective use of their time. All digital resources can be found in one well-organized, easy-to-access place. The IR DVD includes:
  - All textbook images as JPEGs, PDFs, and PowerPoint™ presentations
  - Preauthored Lecture Outline PowerPoint™ presentations, which outline the concepts of each chapter with embedded art and can be customized to fit teachers' lecture requirements
  - CRS "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 also available online via the Instructor Resources section of MasteringMeteorology and **www.pearsonhighered.com/irc**.

- ***Geoscience Animation Library on DVD,* 5th Edition [0321716841] Geoscience Animations** illuminate the most difficult-to-visualize topics from across the physical geosciences, such as solar system formation, hydrologic cycle, plate tectonics, glacial advance and retreat, and global warming. Animations include audio narration and text transcript, with assignable multiple-choice quizzes to select animations in MasteringMeteorology to help students master these core physical process concepts.
- ***Earth Report* Geography Videos on DVD [0321662989]** This three-DVD set is designed to help students visualize how human decisions and behavior have affected the environment and how individuals are taking steps toward recovery. With topics ranging from poor land management promoting the devastation of river systems in Central America to the struggles for electricity in China and Africa, these 13 videos from Television for the Environment's global *Earth Report* series recognize the efforts of individuals around the world to unite and protect the planet. Teachers can assign video clips with assessment in MasteringMeteorology.

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To Lauren, William, and Babsie June

—EA

To my parents, Martha F. Burt
and Robert L. Burt

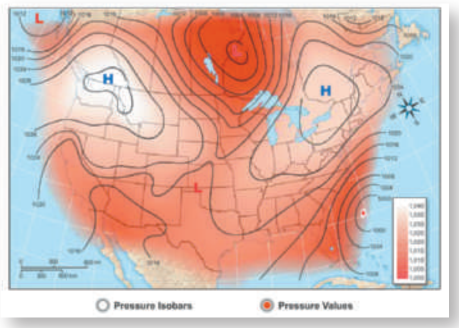
—JEB

PART

1 Energy and Mass

CHAPTER 1

Composition and Structure of the Atmosphere

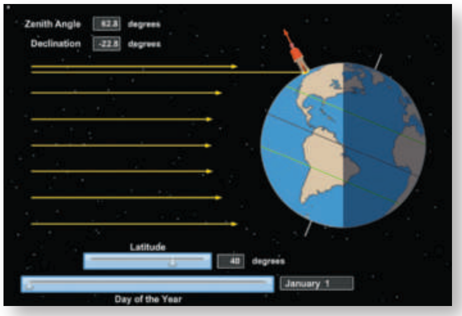


TUTORIAL
Vertical and Horizontal Pressure Variations

How does pressure vary vertically, and what is the explanation?

CHAPTER 2

Solar Radiation and the Seasons

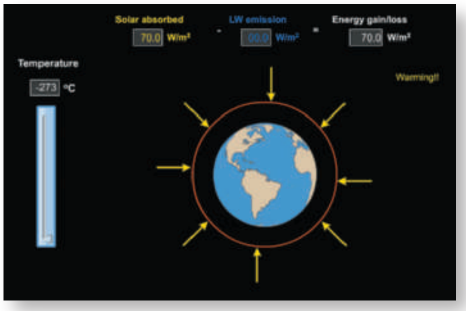


TUTORIAL
Earth–Sun Geometry

How does solar position affect the amount of sunlight reaching the surface?

CHAPTER 3

Energy Balance and Temperature



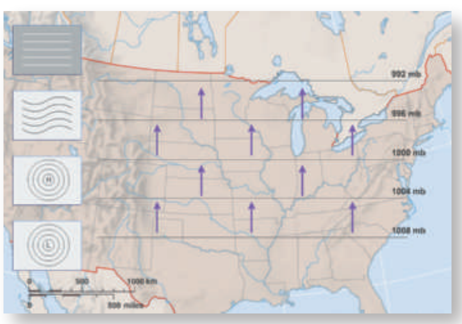
TUTORIAL
Global Energy Balance

What energy fluxes are involved in the energy balance of the surface?

CHAPTER

4

Atmospheric Pressure and Wind



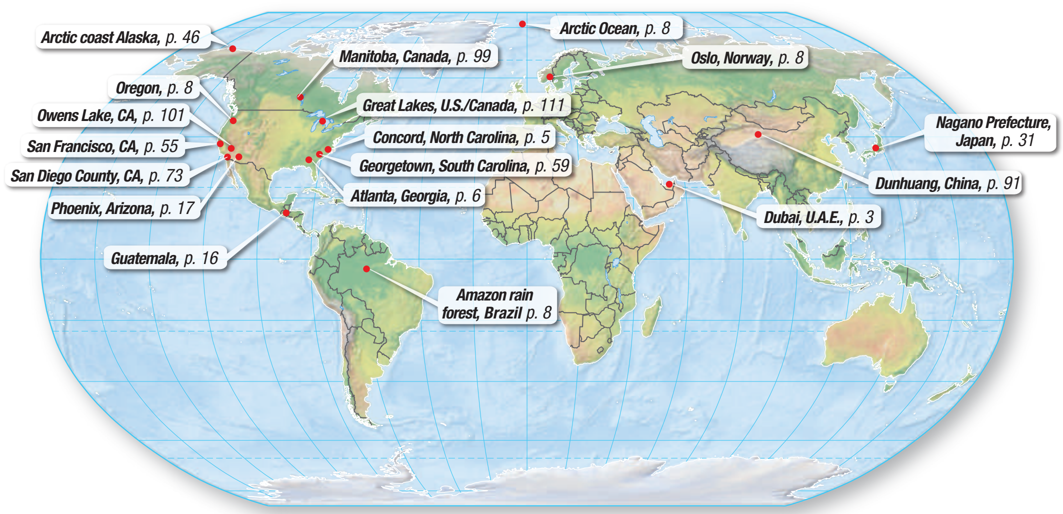
TUTORIAL

Atmospheric Forces and Wind

How do the various forces involved in wind combine to govern wind speed and direction?

◀ *Dense fog at dawn in Dubai, United Arab Emirates. Differences in pressure cause winds to flow onto the land from the surrounding gulf during the day. At night emitted radiation causes water vapor carried by those winds to cool and reach the point of condensation.*

The atmosphere is remarkably variable. Its characteristics are quite different from place to place and from the surface to its upper reaches. It is also subject to subtle movements (such as a gentle breeze) or violent motions (such as tornadoes). After an introduction to the scientific methods used in the study of weather and climate, these chapters look at the composition of the atmosphere and how it is distributed around the planet, how the Sun heats the air, and how pressure and wind patterns are created.



CHAPTER

1 Composition and Structure of the Atmosphere

January 2014 was a brutal month for the eastern United States. Repeated episodes of record and near-record cold struck every state east of the Mississippi. Temperatures of −30 °C (−22 °F) and below prompted thousands of school closings in northern states, and interstate highways were rendered impassible by heavy snows. Late in the month a mix of snow and ice literally paralyzed commuters in Atlanta, and grounded thousands of flights at America's busiest airport. Mainstream media seized on "polar vortex" as the explanation for these cold snaps, deploying a term that had rarely if ever been used before in popular accounts. Commentators on both the political right and left did their best to represent the extreme cold as confirming their views of climate change generally and global warming in particular. Such occurrences are but one example of the atmosphere's importance in human affairs.

◀ *A single storm in mid-February 2014 brought up to 40 cm of snow (16 inches) to parts of North Carolina accustomed to only a few inches in a typical year. Students celebrated school closings (as seen in this photo), but over a million of homes lost power, airports all along the seaboard were paralyzed, and 22 people died as result of the storm.*

Learning Outcomes

After reading this chapter, you should be able to:

1.1 Distinguish between weather and climate.

1.2 Explain the scientific method.

1.3 Describe the thickness of the atmosphere and the vertical distribution of gases within it.

1.4 Describe the behavior of gas molecules in the atmosphere, including residence times and the roles of vertical mixing and gravitational settling.

1.5 Describe the composition of the atmosphere.

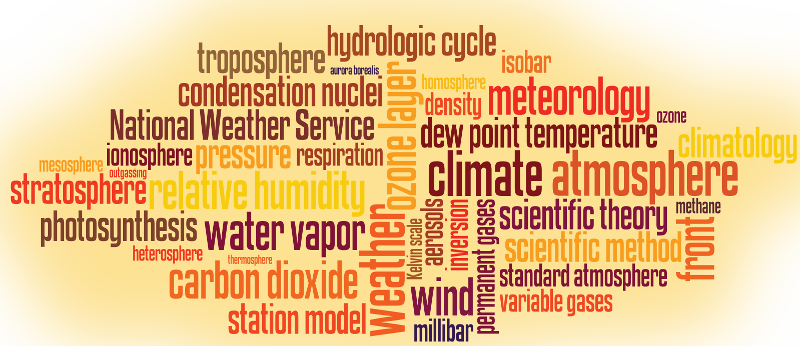
1.6 Explain how air pressure arises and describe the vertical variation of pressure and density.

1.7 Identify and describe the layers of Earth's atmosphere.

1.8 Explain the evolution of the atmosphere during Earth's history.

1.9 Identify the basic types of data found on weather maps.

1.10 List major events in the history of meteorology.



The list of examples includes many other types of disasters that have resulted in huge human and financial costs (Table 1–1). On a personal level none of us is immune to even routine events, whether that means adjusting plans for a picnic or reveling in the beauty of an exceptional sunset.

1–1 FOCUS ON AVIATION

Winter Storms and Air Travel

Video
The Benefits of Doppler Radar
http://goo.gl/wNyeKp

Winter weather can play havoc with air travel in the United States. Naturally, some years are worse than others, and the winter of 2010–2011 was especially difficult. Between November and early February, snow and ice conditions associated with four major storms caused U.S. airlines to cancel some 86,000 flights, with thousands of other flights encountering major delays. These events amounted to a significant portion of all scheduled flights for an industry recovering from some economic difficulties. In December 2010, 3.7 percent of all U.S. flights were cancelled because of winter storms, in contrast to the 2.9 percent cancelled the previous December. Even airports not normally subject to crippling winter storms, such as Hartsfield-Jackson Atlanta International Airport, were subject to the cancellation of thousands of flights when a single January storm left behind 6 inches of snow in a city that usually receives half that much in an entire season (Figure 1–1–1).

▲ **FIGURE 1–1–1 Snowbound Airplanes in Atlanta, January 2011.**

One of the problems associated with winter storms is that aircraft loaded to capacity with passengers can be forced to wait on taxiways between terminal gates and runways for extended periods. For example, the time aircraft must wait before being de-iced contributes to delays. An outcry of consumer criticism led to a policy taking effect in April 2010 that allows the U.S. Department of Transportation to levy fines for air carriers of up to $27,500 per passenger when flights are forced to remain on the tarmac for more than three hours. Some believe this will motivate airlines to cancel flights more readily than in the past, causing greater inconvenience for passengers forced to wait hours or even days for another flight to get them to their destination. On the other hand, passengers are now much less likely to spend half a day on a crowded aircraft just waiting to get to the runway.

Often the disruption of air travel is due to what happens outside the airport during winter weather. Sometimes it is easier for airlines to fly crews in from other areas than it is to wait for scheduled personnel who are delayed by impassable highways on their way to the airport. And of course, flights scheduled to depart San Diego on a warm, sunny day may be unable to do so because the aircraft needed for the flight is stranded at an East Coast airport.

Weather in other seasons also poses different hazards to commercial aviation, as will be discussed in later chapters of this book.

1–1–1 In the depths of winter, what are the approximate chances of your plane being grounded because of weather in the United States? Much less than 1%? A few percent? Between 5% and 10%? More?

1–1–2 Beyond the immediate conditions at an originating airport, what weather-related factors might cause a flight to be cancelled?

Oddly enough, although we are continually surrounded and affected by the atmosphere, most of us know relatively little about how and why the atmosphere behaves as it does. In the chapters that follow, we hope to provide an account of both the how and the why, in ways that will lead you to understand the underlying physical processes. This chapter introduces the most basic elements of meteorology, laying the foundation for much of the rest of the book.

The Atmosphere, Weather, and Climate

1.1 Distinguish between weather and climate.

The **atmosphere** is a mixture of gas molecules, small suspended particles of solid and liquid, and falling precipitation. **Meteorology** is the study of the atmosphere and the processes

TABLE 1–1

Three Decades of Billion-Dollar U.S. Weather Disasters

Dollar Amounts Are Adjusted to 2013 Values											
Year	No. of Events	No. of Deaths	Total Cost	Year	No. of Events	No. of Deaths	Total Cost	Year	No. of Events	No. of Deaths	Total Cost
2013	7	109	23	2003	5	138	17.0	1993	4	338	45.9
2012	11	377	115.6	2002	3	28	17.7	1992	6	87	54.4
2011	14	764	51.3	2001	2	46	9.1	1991	3	43	8
2010	4	46	9.4	2000	2	140	8.1	1990	3	13	9.3
2009	6	26	11.6	1999	5	676	15.2	1989	4	207	21.1
2008	9	296	61.4	1998	7	419	32.4	1988	1	7500	78.8
2007	5	37	12.2	1997	5	114	11.3	1987	0	0	0
2006	6	95	13.5	1996	1	233	20.7	1986	1	21	1.3
2005	5	2002	90.4	1995	4	99	20.8	1985	5	228	11.9
2004	5	172	56.6	1994	6	133	12.6	1984	1	80	1.1

(such as cloud formation, lightning, and wind movement) that cause what we refer to as the "weather." **Weather** is distinct from **climate** in that the former deals with short-term phenomena and the latter with characteristic long-term patterns. A rough analogy can help with the distinction. Most of us have an image of New York's Brooklyn Bridge during the morning rush hour. If our mental picture of slow-moving congestion is the bridge's "traffic climate," weather would be the particular combination of individual cars, buses, and trucks found there on a single day. Take a look outside your window and what you will see is weather. The current temperature, humidity, wind conditions, amount and type of cloud cover, and the presence or absence of precipitation—these are all elements of weather.

DID YOU KNOW?

Tornadoes are not strictly a U.S. phenomenon. Italy, for example, is ranked sixth in the world for tornado density. Twelve were reported in 2012 in an area about the size of Arizona (which had one that year).

Climatology concerns itself with the same elements of the atmosphere that meteorology does, but on a different time scale. Rather than focusing on a single point in time, climatology relies on averages taken over a number of years in order to gauge typical atmospheric conditions for locations across Earth's surface. When people joke about summer conditions as "Sahara-like," they are implicitly making a climatological reference to average conditions in North Africa. Averages are very important, but climatologists also want to know the variability of the weather elements just as, in addition to the average speed, the bridge commuter wants to know about traffic variability. In the case of the atmosphere, it might be useful to know that Boulder, Colorado, has an average April temperature of 7 °C (45 °F), but this figure becomes more meaningful when one understands just how far the temperature might depart from the value on any given day. Frequencies of occurrence of weather events—such as extreme heat, hail, or lightning—are also aspects of climates. Finally, a particularly important part of climatology is concerned with changes in Earth's climate and the factors responsible for those changes.

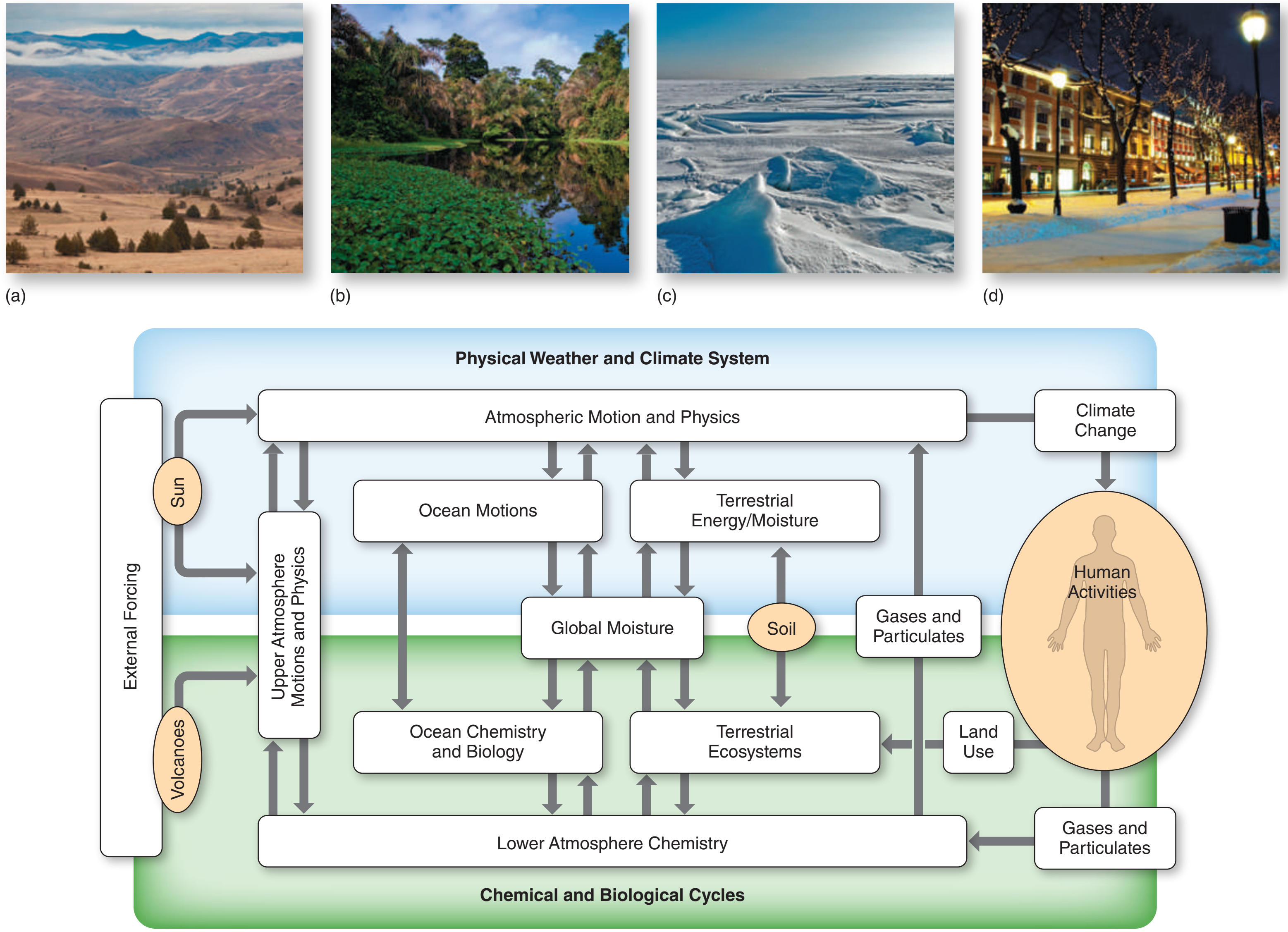
This book's focus on weather and climate correctly suggests that the atmosphere is of primary interest, but we cannot understand our atmospheric environment without reference to land and ocean processes. For example, as illustrated in Figure 1–1, moist Pacific climates in western Oregon give way to desert-like conditions a short distance eastward because of mountain topography. Lush forests in the Amazon basin control a number of processes that are key to the region's climate. Similarly, bright, highly reflective snow and ice surfaces in polar locations contribute greatly to extreme cold. Hurricanes that batter coastal locations could not form without the fuel provided by a warm ocean surface. Western Europe would be frigid if not for the heat imported by ocean currents, and on much longer time scales, large shifts in ocean circulation have led to major climatic changes. Furthermore, the composition of the atmosphere and Earth climate cannot be explained without considering the exchange of material between the solid Earth and the atmosphere. Clearly, an integrated approach that considers all components of the Earth system is necessary. The diagram in Figure 1–1 shows one approach to conceptualizing the components and their interactions. Note the presence of external natural processes and human activities as agents of change.

CHECKPOINT

1.1 Define weather and climate in your own words.

1.2 Compare the concerns of the sciences of meteorology and climatology, giving some examples of different phenomena they might investigate.

1.3 List some places you have visited whose climate is affected by proximity to an ocean or by its position deep within a continent.



▲ **FIGURE 1–1 Earth as a System.** (a–d) These photos show examples of interactions: (a) dryness in Eastern Oregon caused by mountains to the west, (b) dense Amazon vegetation that recycles water between the surface and atmosphere, (c) bright snow enhancing Arctic cold, and (d) ocean currents that make winter in Oslo, Norway, warmer than places much closer to the equator. (e) This figure is a simplified view of the Earth system. The upper part of the diagram represents purely physical aspects of Earth, such as ocean currents, winds, cloud formations, and temperature distributions. The bottom half depicts the constant exchange of material throughout the system, a process known as *cycling*. These exchanges occur between and among the living and nonliving realms, and they both affect and are themselves affected by the physical components of the Earth system.

The Scientific Method and Atmospheric Science

1.2 Explain the scientific method.

Like other physical sciences, meteorology and climatology rely on the **scientific method**. Although it might sound like a strict process, this is really a framework for answering scientific questions. It begins with an inquiry regarding the physical world. For example, having observed tornadoes, we could ask what is responsible for their spin. Or, knowing from landforms glaciers left behind that glaciers have waxed and waned over eons, we might ask if variations in the Sun's output could be involved in glacial outbreaks. Or perhaps we want to know if El Niños (warm episodes in the Tropical Pacific Ocean) affect climate in some other part of the world. The scientific method provides a way to address such questions. It consists of elements that collectively provide us with a way to learn about natural phenomena; it amounts to a convention regarding what it means to "know" something. As individuals we obviously obtain knowledge in various ways; for example, we don't need the scientific method to know that a glowing ember will burn one's hand. The scientific method, however, is particularly useful when our goals are to obtain a shared understanding and to resolve ambiguity. On a purely practical level, its value has been proven over centuries of use, and everyday life abounds with discoveries and inventions that would have been impossible to achieve otherwise.

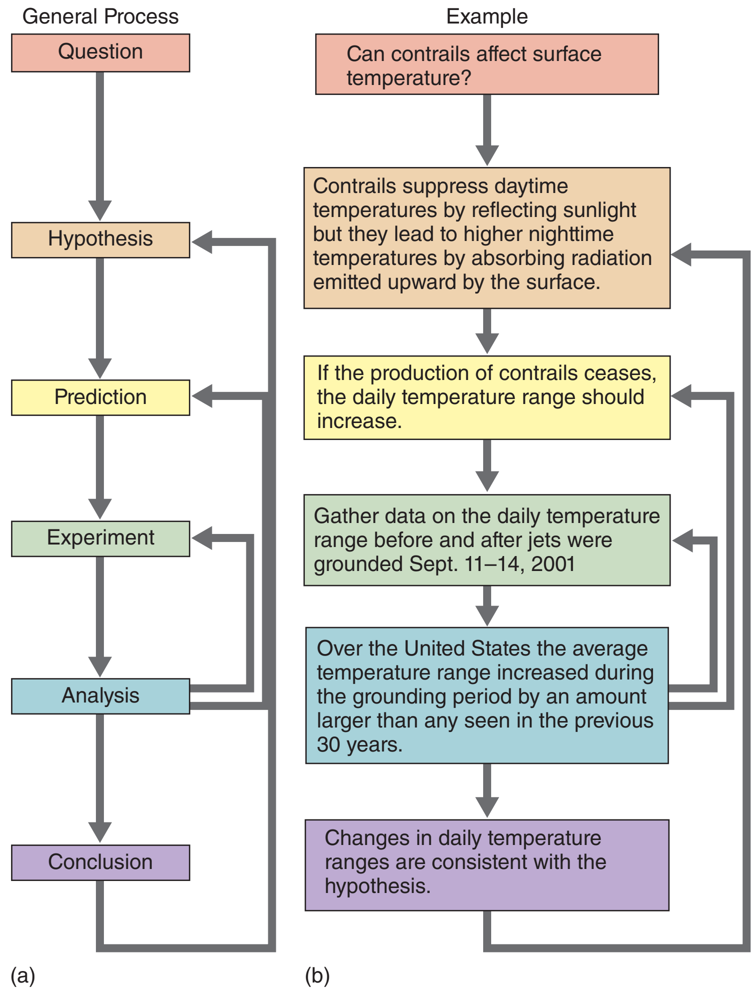
Applying the Scientific Method

The scientific method has the following elements: question, hypothesis, prediction, experiment, analysis, and conclusion (Figure 1–2a). To illustrate these elements, we will use research from about a decade ago concerning the climatic effects of jet aircraft (Figure 1–2b).[1] In particular, researchers wanted to investigate the possibility that clouds produced by aircraft (contrails) could influence temperature near the ground. Thus for this example, the question is simply "Can contrails affect surface temperature?" The idea that clouds produced by aircraft contrails could influence temperature near the surface had been debated for decades, but the grounding of aircraft in the United States following the U.S. terrorist attacks in 2001 provided a chance to study the question in a new way. In particular, the sudden absence of jet contrails offered a "before and after" test covering the entire country.

Hypotheses follow from the question and play a particularly important role in the scientific method. They can be proposed explanations for previously observed measurements, or claims about the role of some process in a phenomenon of interest. By definition, scientific hypotheses must be testable. If there is no conceivable way of evaluating a hypothesis, it has no role in the scientific method. As a practical matter this means the hypothesis must lead to predictions. In the contrails example the hypothesis specifies how contrails would affect surface temperatures. Based on prior knowledge about radiation transfer in the atmosphere, it amounts to an educated guess about how contrails might exert influence on air temperature near the ground.

Predictions can be a forecast of what will happen in the future, but more commonly are statements about what one should observe if particular data are analyzed. The important thing is that predictions are logical consequences that follow from hypotheses. The *experiment* can be a procedure performed in a laboratory, or a computer simulation, or anything else that produces data bearing on the prediction. In the contrail example, the "experiment" was to compile air temperature data from weather stations throughout the continental United States. In this case the experiment was almost trivial, because it merely required retrieval of air temperature data routinely collected for other purposes. But easy or not, the experimental methods must be clearly described. In this case it meant documenting the data (how many weather stations, where, etc.). In other cases it could mean describing the computer model used to generate new data or describing exactly what measurement procedures were used.

The *analysis* step evaluates the predictions and thereby renders information about the hypotheses, which is reflected



▲ **FIGURE 1–2 Elements of the Scientific Method in (a) General Terms and Illustrated by an (b) Example.**

in the *conclusion*. In this example, analysis showed that the grounding period was highly unusual: The average day–night temperature range increased dramatically during the grounding period. In fact, the increase was larger than in any of the prior 30 years. As explained in the figure, a larger range is expected based on the hypothesis. Thus, the analysis supports the hypothesized connection between jet contrails and air temperature. Here again the methods used must be clearly specified. The reason is that reproducibility is a critical aspect of the scientific method. Other researchers employing the same methods must achieve the same outcomes. If some aspect of the process were to depend on the particular individuals involved it would not be scientific. In other words, things such as a researcher's experience, reputation, "common sense," and ability to provide deep insights do not carry any weight when it comes to confirming or refuting hypotheses.

Variations on the Scientific Method

The scientific method is often presented as a sequence of steps, and it is true that the outcomes of a scientific study can usually be placed in the categories shown in Figure 1–2.

[1]Travis, David J., Andrew M. Carleton, and Ryan G. Lauritsen, "Contrails Reduce Daily Temperature Range," *Nature*, 418 (2002), p. 601.