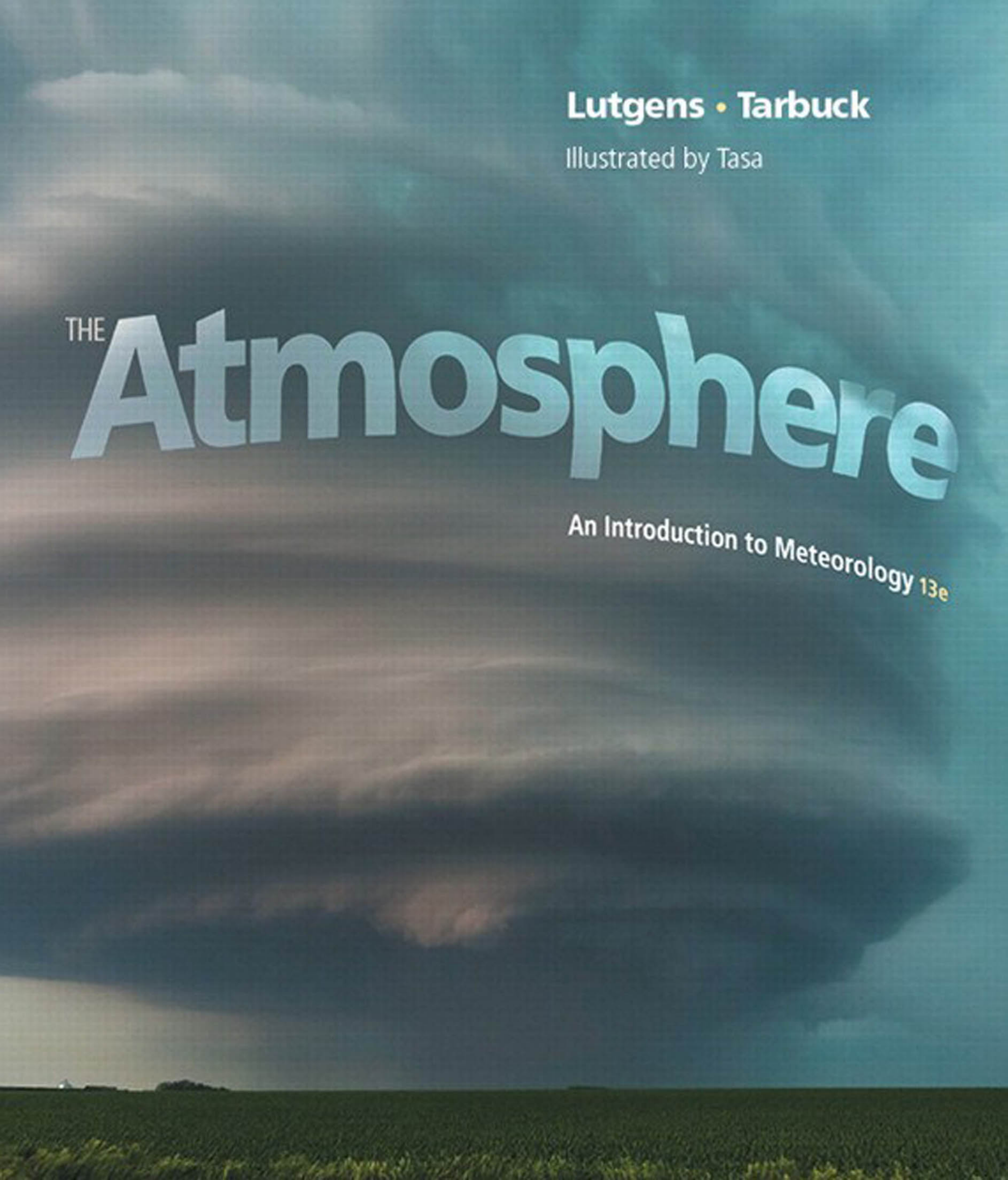
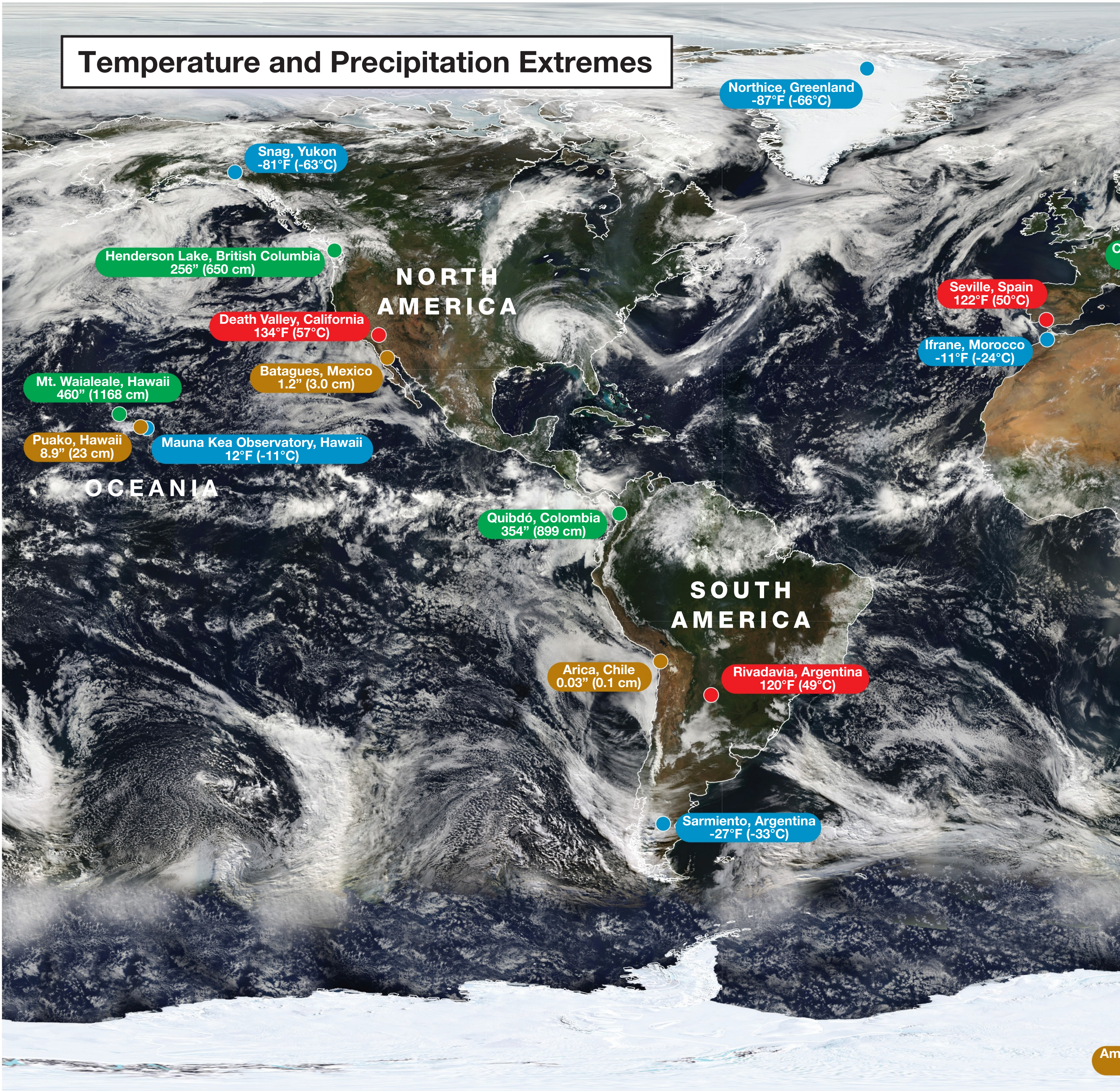


Lutgens • Tarbuck

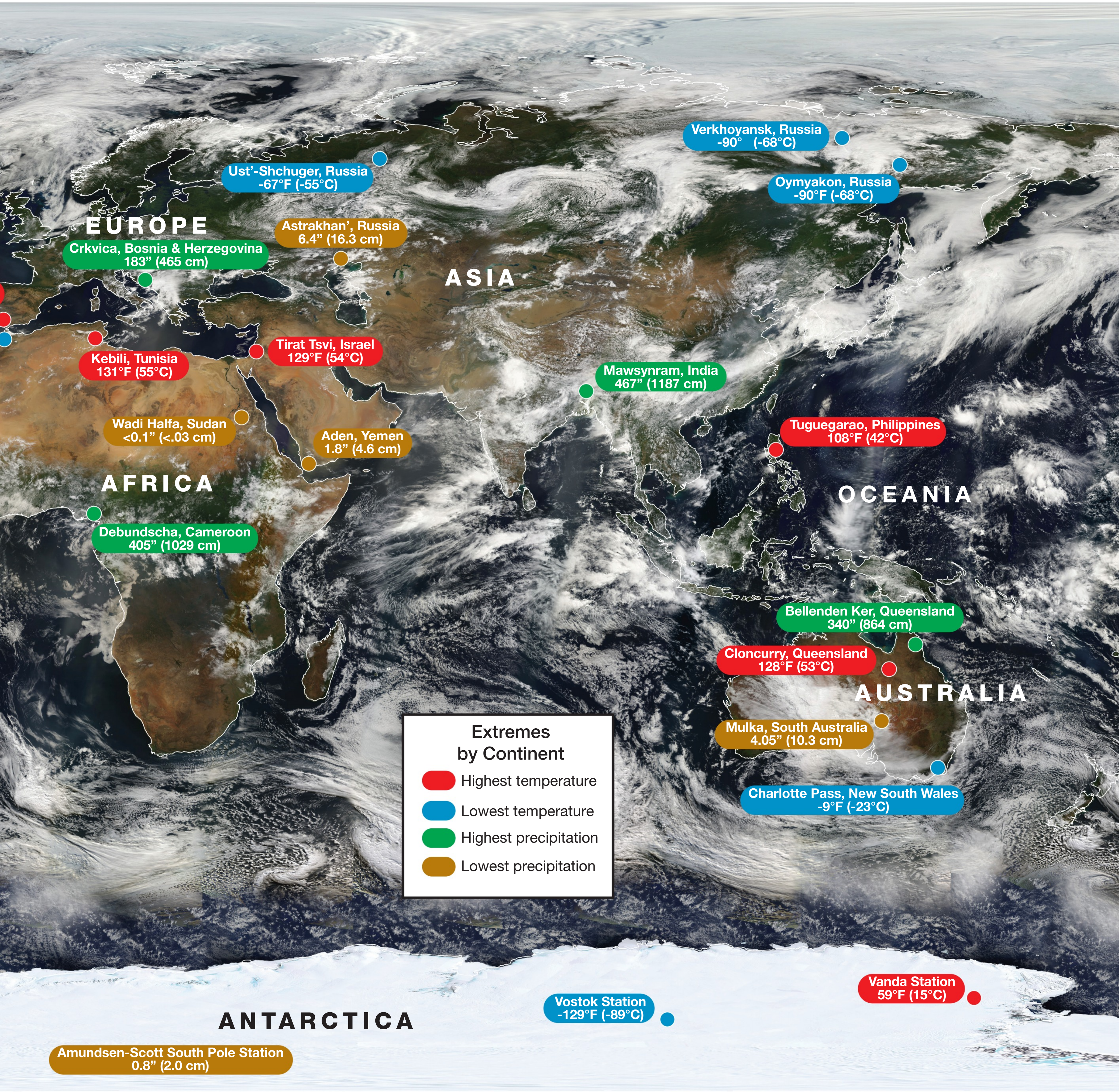
Illustrated by Tasa

THE Atmosphere

An Introduction to Meteorology 13e



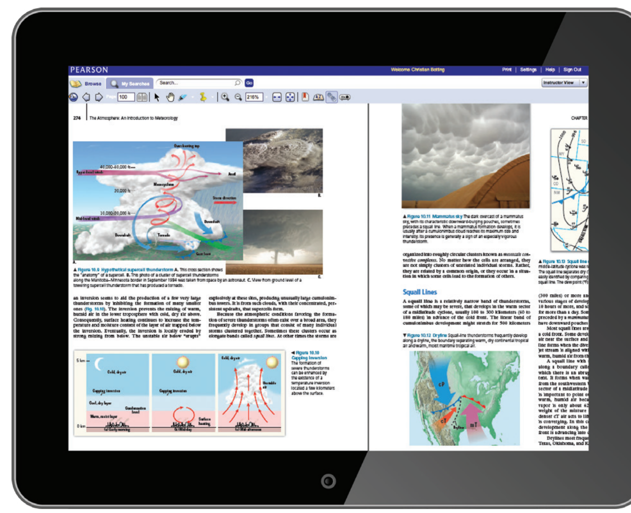
This photo-like view is based largely on observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASAs *Terra* satellite.


EUROPE
ASIA
AFRICA
OCEANIA
AUSTRALIA
ANTARCTICA
Ust'-Shchuger, Russia
-67°F (-55°C)
Verkhoyansk, Russia
-90° (-68°C)
Oymyakon, Russia
-90°F (-68°C)
Astrakhan', Russia
6.4" (16.3 cm)
Crkvica, Bosnia & Herzegovina
183" (465 cm)
Kebili, Tunisia
131°F (55°C)
Tirat Tsvi, Israel
129°F (54°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)

So Many Options for Your Meteorology Class!

Students today want options when it comes to their textbooks. *The Atmosphere* gives students the flexibility they desire, offering a wide range of formats for the book, and a large array of media and online learning resources. Find a version of the book that works best for YOU!

Whether it's on a laptop, tablet, smartphone, or other wired mobile devices, *The Atmosphere* lets students access media and other tools for learning meteorology.



The Atmosphere Plus MasteringMeteorology with eText

ISBN 0-321-98914-7 / 978-0-321-98914-7

Available at no additional charge with MasteringMeteorology, the Pearson eText version of *The Atmosphere*, 13th Edition, gives students access to the text whenever and wherever they are online. Features of Pearson eText:

- Now available on smartphones and tablets.
- Seamlessly integrated videos and other rich media.
- Fully accessible (screen-reader ready).
- Configurable reading settings, including resizable type and night reading mode.
- Instructor and student note-taking, highlighting, bookmarking, and search functionality.

The Atmosphere CourseSmart eTextbook

ISBN 0-134-01601-7 / 978-0-134-01601-6

CourseSmart eTextbooks are an alternative to purchasing the print textbook, where students can subscribe to the same content online and save up the 40% off the suggested list price of the print text.

The Atmosphere Books à La Carte

ISBN 0-321-98714-4 / 978-0-321-98714-3

Books à la Carte features the same exact content as *The Atmosphere* in a convenient, three-hole-punched, binder-ready, loose-leaf version. Books à la Carte offers a great value for students—this format costs 35% less than a new textbook package.

Pearson Custom Library: You Create Your Perfect Text

http://www.pearsoncustomlibrary.com

The Atmosphere is available on the Pearson Custom Library, allowing instructors to create the perfect text for their courses. Select the chapters you need, in the sequence you want. Delete chapters you don't use: students pay only for the materials chosen.

MasteringMeteorology Student Study Area

No matter the format, with each new copy of the text, students will receive full access to the Study Area in MasteringMeteorology™, providing a wealth of Animations, Videos, MapMaster™ Interactive Maps, GEODe Tutorials, *In the News* readings, Flashcards, practice quizzes, and much more.

This page intentionally left blank

The Perfect Storm of Rich Media & Active Learning Tools

with

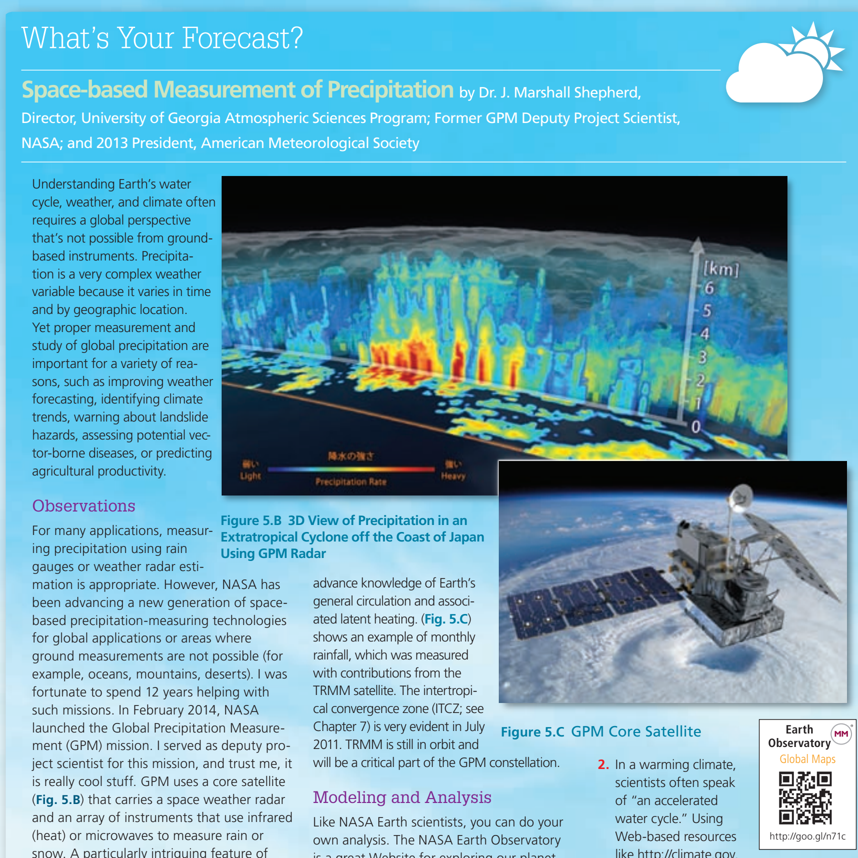
The Atmosphere: An Introduction to Meteorology

&

MasteringMeteorology™

Real World Applications

The dynamic revision of *Atmosphere: An Introduction to Meteorology* incorporates the latest science, a new active-learning approach, integrated mobile media, and MasteringMeteorology™, the most complete, easy-to-use, engaging tutorial, media, and assessment platform available.


What's Your Forecast?

Space-based Measurement of Precipitation by Dr. J. Marshall Shepherd, Director, University of Georgia Atmospheric Sciences Program; Former GPM Deputy Project Scientist, NASA; and 2013 President, American Meteorological Society

Understanding Earth's water cycle, weather, and climate often requires a global perspective that's not possible from ground-based instruments. Precipitation is a very complex weather variable because it varies in time and by geographic location. Yet proper measurement and study of global precipitation are important for a variety of reasons, such as improving weather forecasting, identifying climate trends, warning about landslide hazards, assessing potential vector-borne diseases, or predicting agricultural productivity.

Figure 5.B 3D View of Precipitation in an Extratropical Cyclone off the Coast of Japan Using GPM Radar

Observations

For many applications, measuring precipitation using rain gauges or weather radar estimation is appropriate. However, NASA has been advancing a new generation of space-based precipitation-measuring technologies for global applications or areas where ground measurements are not possible (for example, oceans, mountains, deserts). I was fortunate to spend 12 years helping with such missions. In February 2014, NASA launched the Global Precipitation Measurement (GPM) mission. I served as deputy project scientist for this mission, and trust me, it is really cool stuff. GPM uses a core satellite (Fig. 5.B) that carries a space weather radar and an array of instruments that use infrared (heat) or microwaves to measure rain or snow. A particularly intriguing feature of

advance knowledge of Earth's general circulation and associated latent heating. (Fig. 5.C) shows an example of monthly rainfall, which was measured with contributions from the TRMM satellite. The intertropical convergence zone (ITCZ; see Chapter 7) is very evident in July 2011. TRMM is still in orbit and will be a critical part of the GPM constellation.

Figure 5.C GPM Core Satellite

Modeling and Analysis

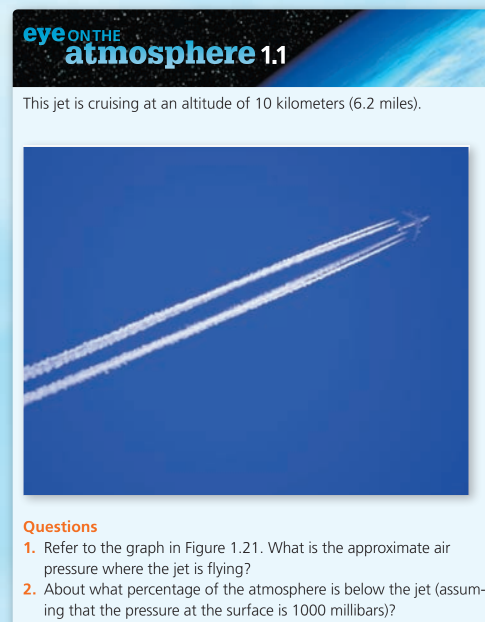
Like NASA Earth scientists, you can do your own analysis. The NASA Earth Observatory is a great Website for exploring our planet

2. In a warming climate, scientists often speak of "an accelerated water cycle." Using Web-based resources like http://climate.gov,

Earth Observatory
Global Maps
http://goo.gl/n71c

NEW! What's Your Forecast?

What's Your Forecast? features authored by expert contributors include active learning forecast activities tied to chapter content where students make predictions based on real-world scenarios and data.


eye on the atmosphere 1.1

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

Questions

1. Refer to the graph in Figure 1.21. 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)?


eye on the atmosphere 4.1

Water is everywhere on Earth—in the oceans, glaciers, rivers, lakes, air, and living tissue. In addition, water can change from one state of matter to another at the temperatures and pressures experienced on Earth. Refer to this image, taken above the Grand Tetons, Wyoming, to answer the following questions.

Questions

1. What feature in this photo is composed of water in the liquid state?
2. Name the process by which ice changes directly from a solid to water vapor.
3. Identify where water vapor is found in this image.

UPDATED! Eye on the Atmosphere

Eye On The Atmosphere feature boxes engage students with active learning tasks, asking them to observe, perform critical visual analysis, and make predictions—core behavioral goals of this course.

Engaging & Empowering Students

Severe and Hazardous Weather ▸

The text contains 15 *Severe and Hazardous Weather* features devoted to a broad variety of topics—heat waves, winter storms, floods, air pollution episodes, drought, wildfires, cold waves, and more.


severe& hazardous weather Box 5.1

Worst Winter Weather

Extremes, whether the *tallest* building or the *record low temperature* for a location, fascinate many humans. When it comes to weather, some places take pride in claiming to have the worst winters on record. In fact, both Fraser, Colorado, and International Falls, Minnesota, have proclaimed themselves the "ice box of the nation." Although Fraser recorded the lowest temperature for the 48 contiguous states 23 times in 1989, its neighbor Gunnison, Colorado, recorded the lowest temperature 62 times, far more than any other location.

Such facts do not impress the residents of Hibbing, Minnesota, where the temperature dropped to −38°C (−37°F) during the first week of March 1989. But this is mild stuff, say the old-timers in Parshall, North Dakota, where the temperature fell to −51°C (−60°F) on February 15, 1936. Not to be left out, Browning, Montana, holds the record for the most dramatic 24-hour temperature drop. Here the temperature plummeted 56°C (100°F), from a cool 7°C (44°F) to a frosty −49°C (−56°F) during a January evening in 1916.

Although impressive, the temperature extremes cited here represent only one aspect of winter weather.

Although impressive, the temperature extremes cited here represent only one aspect of winter weather. What about snowfall (Fig. 5.A)? Cooke City holds the seasonal snowfall record for Montana, with 1062 centimeters (418.1 inches) during the winter of 1977–1978. But what about cities like Sault Ste. Marie, Michigan, and Buffalo, New York? The winter snowfalls associated with the Great Lakes are legendary. Even larger snowfalls occur in many sparsely inhabited mountainous areas.

Try telling residents of the eastern United States that heavy snowfall alone makes for the worst weather. A blizzard in March 1993 produced heavy snowfall along with hurricane-force winds and

▲ Figure 5.A A winter snowstorm of historic proportions struck Chicago, Illinois, on February 2, 2011.


Box 3.1 North America's Hottest and Coldest Places

Most people living in the United States have experienced temperatures of 38°C (100°F) or more. When statistics for the 50 states are examined for the past century or longer, we find that every state has a maximum temperature record of 38°C or higher. Even Alaska has recorded a temperature this high—set June 27, 1915, at Fort Yukon, a town along the Arctic Circle in the interior of the state.

Maximum Temperature Records

Surprisingly, the state that ties Alaska for the "lowest high" is Hawaii. Panala, on the south coast of the Big Island, recorded 38°C on April 27, 1931. Although humid tropical and subtropical places such as Hawaii are known for being warm throughout the year, they seldom experience maximum temperatures that surpass the low to mid-30s Celsius (90s Fahrenheit).

The highest accepted temperature record for the United States as well as the entire world is 57°C (134°F). This long-standing record was set at Death Valley, California, on July 10, 1913. Summer temperatures at Death Valley are consistently among the highest in the Western Hemisphere. During June, July, and August, temperatures exceeding 49°C (120°F) are to be expected. Fortunately, Death Valley has few human summertime residents (Fig. 3.A).

Why are summer temperatures at Death Valley so high? In addition to having the lowest elevation in the Western Hemisphere (53 meters [174 feet] below sea level), Death Valley is a desert. Although it is only about 300 kilometers (less than 200 miles) from the Pacific Ocean, mountains cut off the valley from the ocean's moderating influence and moisture. Clear skies allow a maximum of sunshine to strike the dry, barren surface. Because no energy is used to evaporate moisture, as occurs in humid regions, all the energy is available to heat the ground. In addition, subsiding air that warms by compression as it descends is also common to the region and contributes to its high maximum temperatures.

Minimum Temperature Records

The temperature controls that produce truly frigid temperatures are predictable and should come as no surprise. We expect extremely cold temperatures during winter in high-latitude places that lack the moderating influence of the ocean. Moreover, stations located on ice sheets and glaciers should be especially cold, as should stations positioned high in the mountains. All these criteria apply to Greenland's North Ice Station (elevation 2307 meters [7567 feet]). Here on January 9, 1954, the temperature plunged to −66°C (−87°F). If we exclude Greenland from consideration, Snag, in Canada's Yukon, holds the record for North America. This remote outpost experienced a temperature of −63°C (−81°F) on February 3, 1947. When only U.S. locations are considered,

▲ Figure 3.A Almost a record! On June 30, 2013, 100 years after Death Valley set the all-time high recorded temperature, it came close to equaling it. On that date, Death Valley's air temperature peaked at 54°C (129.2°F).

Prospect Creek, located north of the Arctic Circle in the Endicott Mountains of Alaska, came close to the North American record on January 23, 1971, when the temperature plunged to −62°C (−80°F). In the lower 48 states, the record of −57°C (−70°F) was set in the mountains at Rogers Pass, Montana, on January 20, 1954. Remember that many other places have no doubt experienced equally low or even lower temperatures; they just were not recorded.

Question

1. Death Valley is not a great distance from the cool Pacific Ocean yet experiences very high temperatures. Why is there no moderating ocean influence?

Students Sometimes Ask... ▾

Students Sometimes Ask features are integrated throughout the chapters, addressing high-interest topics and common student misconceptions.

students sometimes ask...

If Earth's atmosphere had no greenhouse gases, what would surface-air temperatures be like?

Cold! Earth's average surface temperature would be a chilly −18°C (−0.4°F) instead of the relatively comfortable 14.5°C (58°F) that it is today.

Special Feature Box ▴

Special Feature Boxes throughout the chapters present compelling case studies or further illuminate interesting concepts discussed.

◂ Cloud Guide

A foldout cloud guide at the back of the book provides students with a tool and reference for real-world observation.

Global Climate Change

This new edition features extended coverage of global climate change and includes the findings of the IPCC's 5th Assessment Report.

◂Our Changing Climate

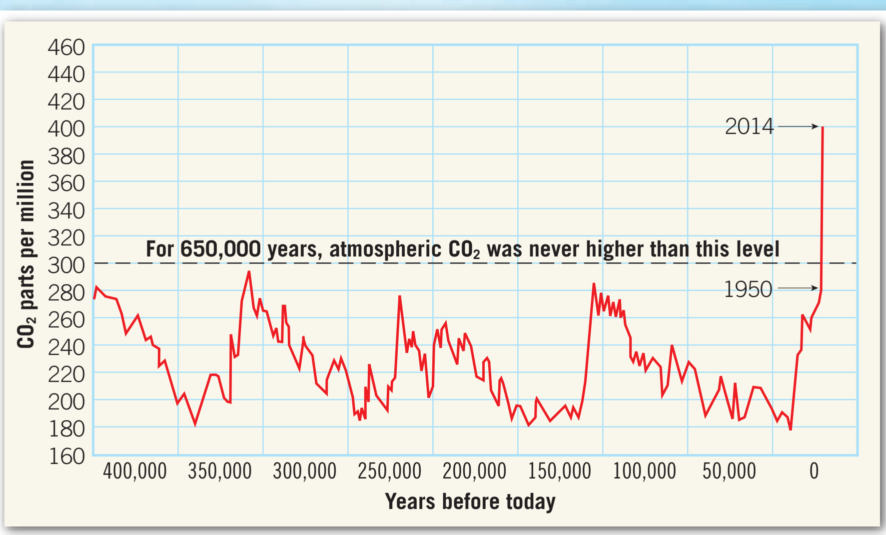
The latest data and applications related to global climate change are presented throughout the 13th edition, for the most current and comprehensive coverage.

Thunderstorms and Climate Change

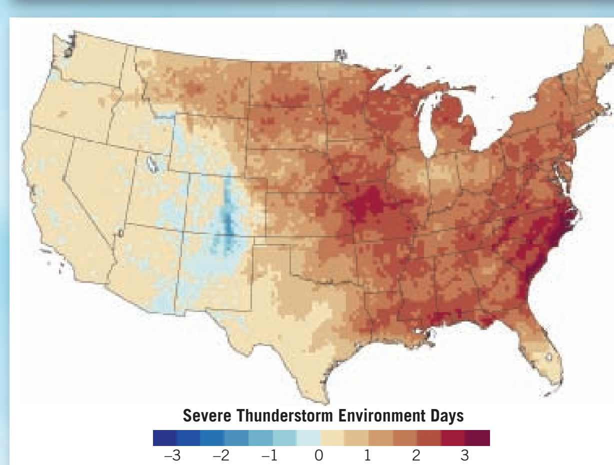
In the preceding discussion, you learned that the occurrence of thunderstorms varies seasonally and from place to place. Thunderstorm activity will likely increase in many areas in the years to come due to global climate change. Global temperatures have been warming for decades largely due to human activities that are altering the composition of the atmosphere. This trend is expected to continue for the foreseeable future. A thorough discussion of this phenomenon appears in Chapter 14.

Video MM
Thundersleet and Thundersnow
http://goo.gl/GOm7IV

MM MapMaster ▶ North America Physical Environment ▶ Thunderstorm Occurrence Per Year



▲ **Figure 14.22 CO_2 concentrations over the past 400,000 years** Most of these data come from analyses of air bubbles trapped in ice cores. The record since 1958 comes from direct measurements at Mauna Loa Observatory, Hawaii. The rapid increase in CO_2 concentrations since the onset of the Industrial Revolution is obvious. (NOAA)



▲ **Figure 10.4 Future thunderstorm activity** This map shows changes in the number of days per year when the environmental conditions that promote severe thunderstorm activity occur. The map is based on a climate model comparing summer climate during 2072–2099 with a similar span during 1962–1989. Most of the area east of the Rocky Mountains is projected to experience an increase in these environmental conditions.

Projected Impacts of Climate Change▴

Integrated coverage of the findings and data of the 2013-2014 IPCC 5th Assessment Report are presented throughout the chapters, including discussion of possible future scenarios for Earth's climate.

Structured Learning

The 13th Edition provides an active structured learning path to help guide students toward mastery of key meteorological concepts.

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:

3.1 Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms.

3.2 Name the principal controls of temperature and use examples to describe their effects.

3.3 Interpret the patterns depicted on world temperature maps.

3.4 Discuss the basic daily and annual cycles of air temperature.

3.5 Explain how different types of thermometers work and why the placement of thermometers is an important factor in obtaining accurate readings. Distinguish among Fahrenheit, Celsius, and Kelvin temperature scales.

3.6 Summarize several applications of temperature data.

◀ UPDATED! Focus on Concepts

Focus on Concepts learning goals are listed in the chapter-opening spreads and correlate to Concept Check and GIST questions to help students focus on and prioritize the learning goals for each chapter.

✔ Concept Checks 14.3

1. Why has the CO_2 level of the atmosphere been increasing over the past 200 years?
2. How has the atmosphere responded to the growing CO_2 levels? How are temperatures in the lower atmosphere likely to change as CO_2 levels continue to increase?
3. Aside from CO_2, what trace gases are contributing to global temperature change?
4. List the main sources of human-generated aerosols and describe their net effect on atmospheric temperatures.

UPDATED! Give It Some Thought ▼

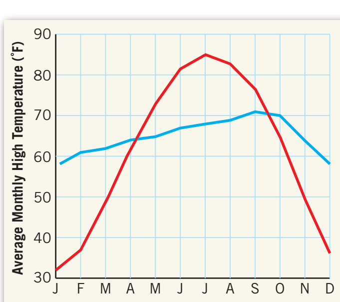
Give It Some Thought (GIST) questions are found at the end of each chapter and ask students to use higher-level thinking. They often involve chapter visuals, which help students apply and synthesize entire chapter concepts.

UPDATED! Concept Checks ▲

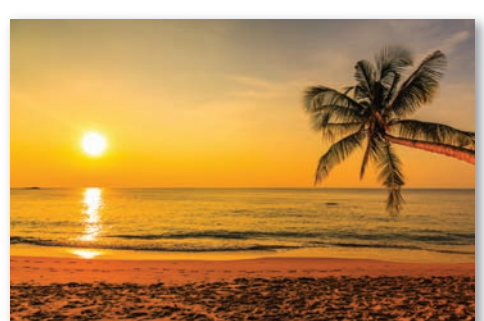
Concept Check questions are integrated throughout each chapter. These serve as conceptual speed bumps, asking students to assess their understanding as they are reading.

Give it Some Thought

1. If you were asked to identify the coldest city in the United States (or any other designated region), what statistics could you use? Can you list at least three different ways of selecting the coldest city?
2. The accompanying graph shows monthly high temperatures for Urbana, Illinois, and San Francisco, California. Although both cities are located at about the same latitude, the temperatures they experience are quite different. Which line on the graph represents Urbana, and which represents San Francisco? How did you figure this out?



3. On which summer day would you expect the greatest temperature range? Which would have the smallest range in temperature? Explain your choices.
   a. Cloudy skies during the day and clear skies at night
   b. Clear skies during the day and cloudy skies at night
   c. Clear skies during the day and clear skies at night
   d. Cloudy skies during the day and cloudy skies at night
4. The accompanying scene shows an island near the equator in the Indian Ocean. Describe how latitude, altitude, and the differential heating of land and water influence the climate of this place.



Continuous Learning Before, During & After Class with MasteringMeteorology

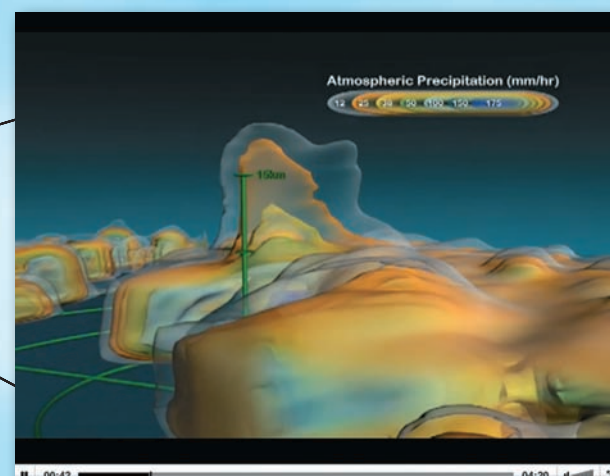
BEFORE CLASS

Mobile Media and Reading Assignments Ensure Students Come to Class Prepared

NEW! Mobile-Enabled Videos and Animations (QR)▸

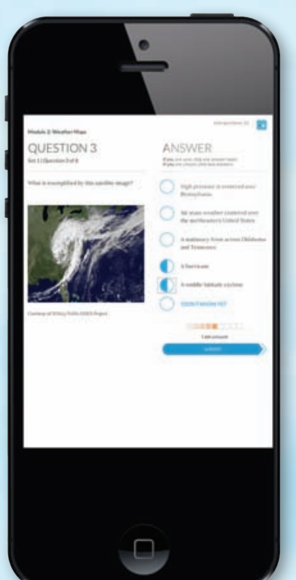
Mobile-Enabled Quick Response (QR) codes integrated throughout chapter sections empower students to use their mobile devices for learning as they read, providing instant access to over 130 SmartFigures, Videos, and Animations of real-world atmospheric phenomena and visualizations of key physical processes. These media can be assigned with quizzes in MasteringMeteorology.

Video
MM
Hot Towers and Hurricane Intensification
http://goo.gl/jJmpo



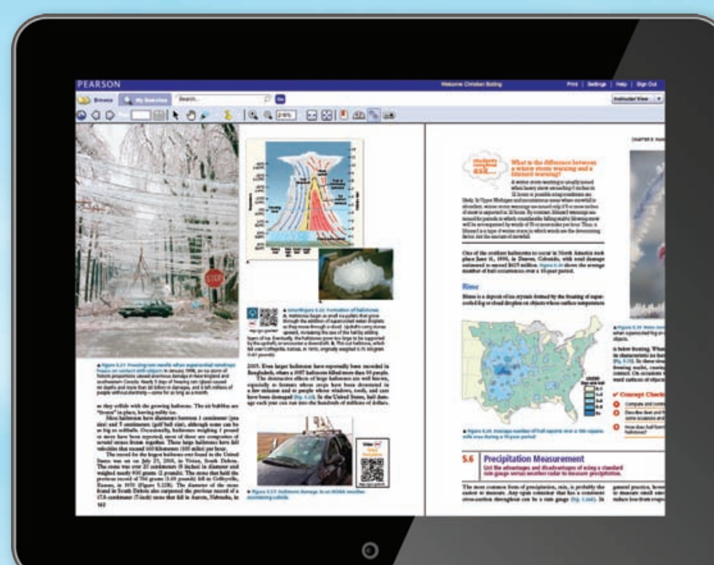
NEW! Dynamic Study Modules▸

Dynamic Study Modules personalize each student's learning experience. Created to allow students to acquire knowledge on their own and be better prepared for class discussions and assessments, this mobile app is available for iOS and Android devices.



eText▸

Pearson eText in MasteringMeteorology gives students access to the text whenever and wherever they can access the internet. Users can create notes, highlight text, create bookmarks, zoom and click hyperlinked words, phrases or media to view definitions, websites or view Pearson videos and animations.



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

NEW! Reading Questions 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 mobile devices.

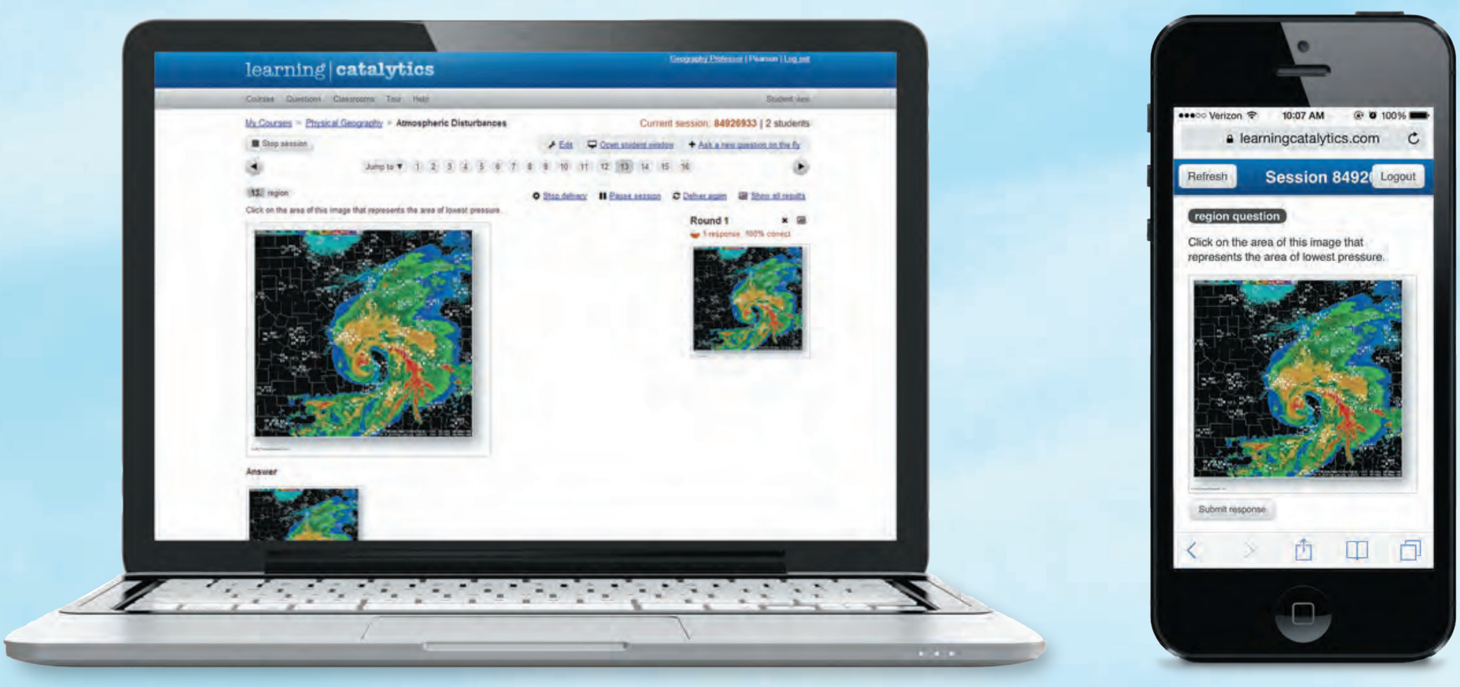
DURING CLASS

Learning Catalytics

"My students are so busy and engaged answering Learning Catalytics questions during lecture that they don't have time for Facebook"
Declan De Paor, Old Dominion University

What has Professors and Students excited? Learning Cataltyics, 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 Cataltyics, you 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

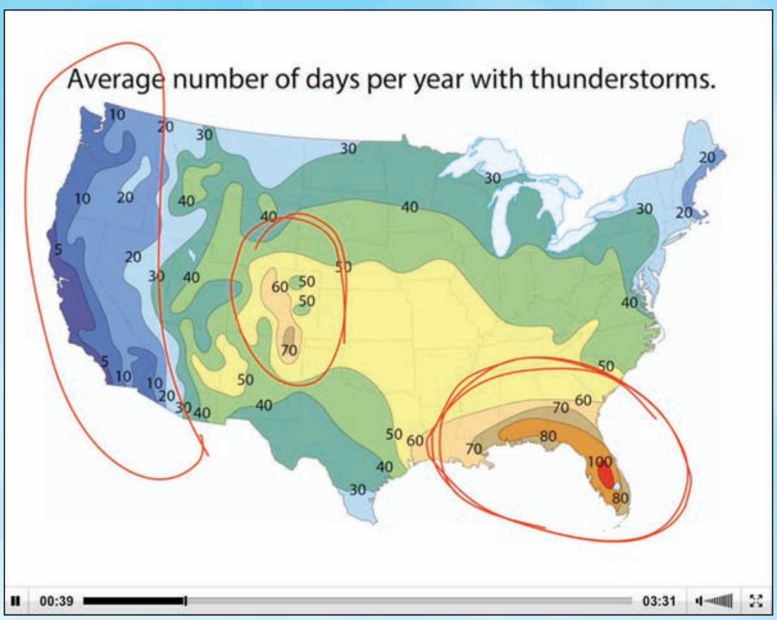
Teachers can incorporate dynamic media into lecture, such as Geoscience Animations, Videos, and MapMaster Interactive Maps.

MasteringMeteorology™

AFTER CLASS

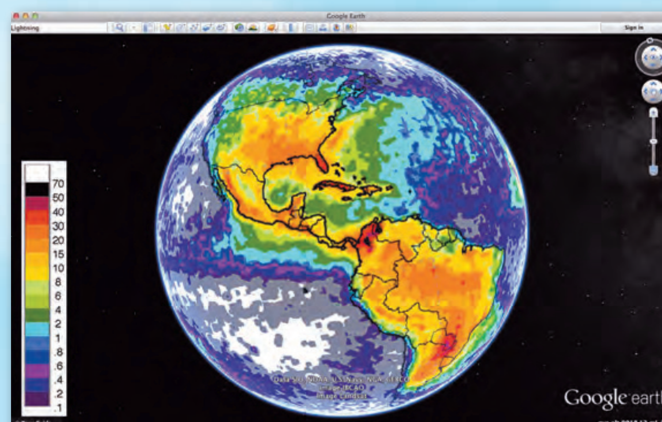
Easy to Assign, Customizable, Media-Rich, and Automatically Graded Assignments

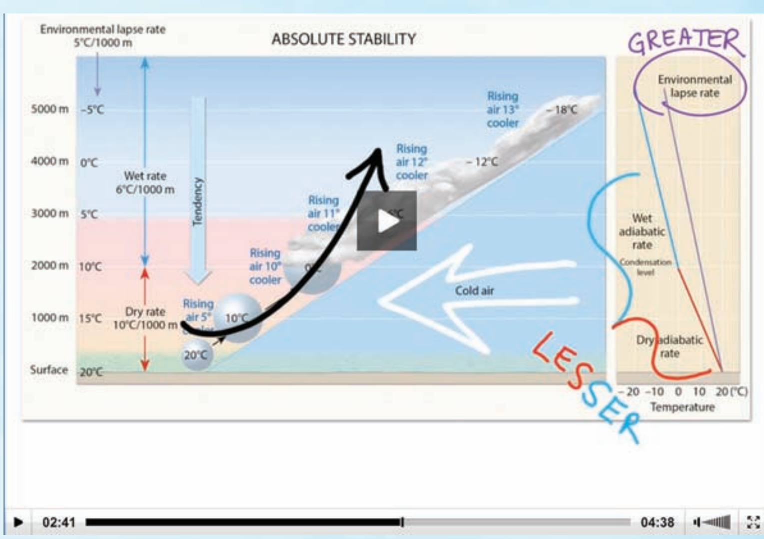
The breadth and depth of media content available in MasteringMeteorology is unparalleled, allowing teachers to quickly and easily assign homework to reinforce key concepts. Most media activities are supported by automatically-graded multiple choice quizzes with hints and specific wrong answer feedback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



Encounter Activities▼

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



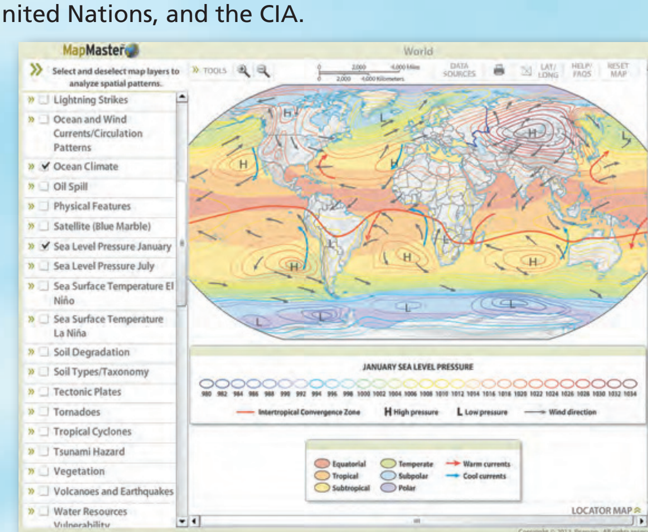


SmartFigures▲

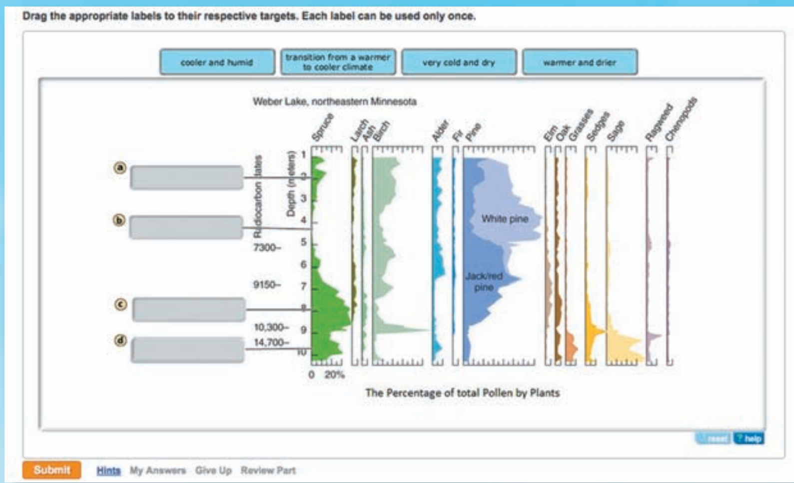
SmartFigures are brief, narrated video lessons that examine and explain concepts illustrated by key figures within the text. Students access SmartFigures on their mobile devices by scanning Quick Response (QR) codes next to key figures. These media are also available in the Study Area of MasteringMeteorology and teachers can assign them with automatically-graded quizzes.

MapMaster Interactive Map Activities▼

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.

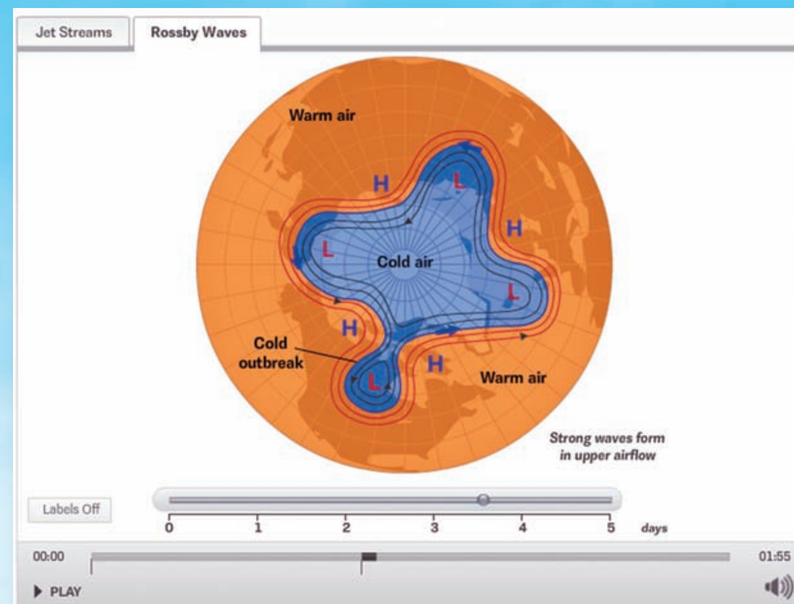


MasteringMeteorology™



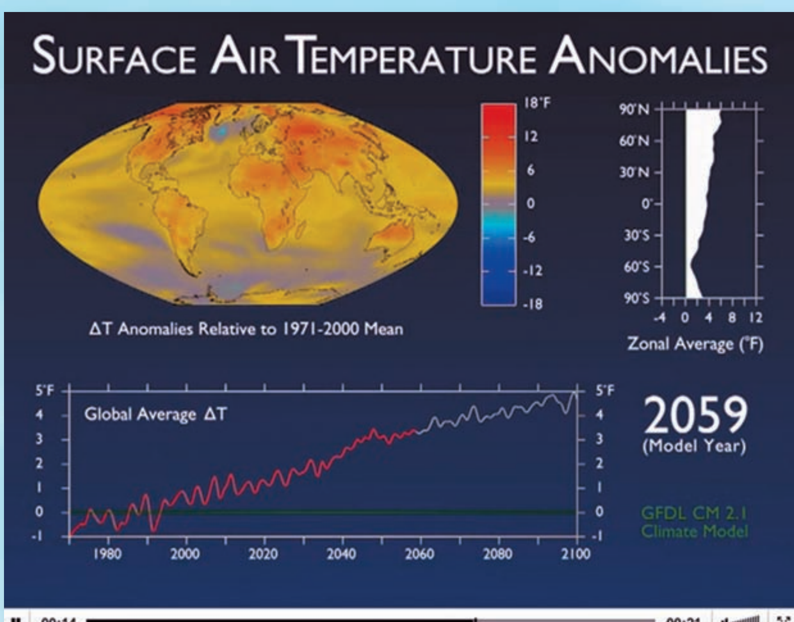
NEW! GeoTutors▲

These 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.



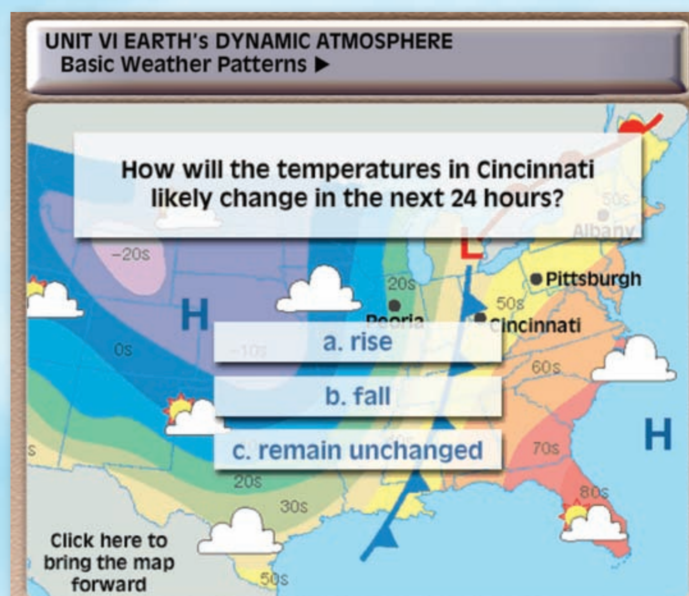
Geoscience Animations Activities▲

Geoscience Animation Activities help students visualize the most challenging physical processes in the physical geosciences with schematic animations that include audio narration.



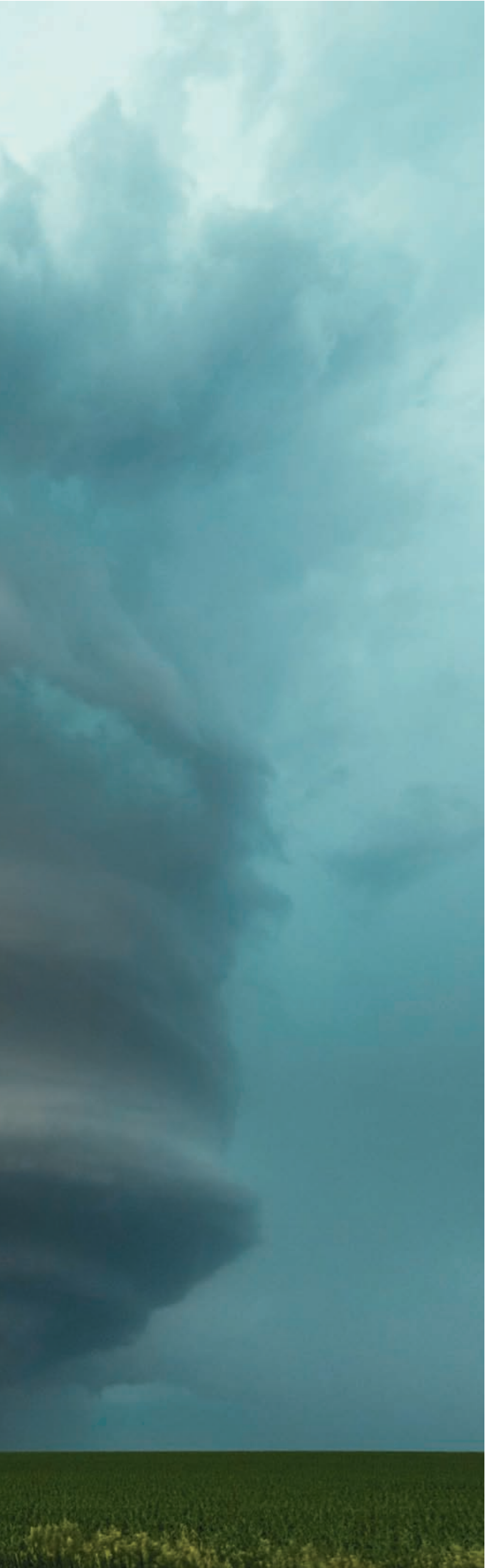
NEW! Videos▲

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



GEODe: Atmosphere▲

GEODe: Atmosphere is a dynamic program that reinforces key meteorological concepts through animations, tutorials, interactive exercises, and review quizzes.



THE

Atmosphere 13e

An Introduction to Meteorology

Frederick K. Lutgens

Edward J. Tarbuck

Illustrated by Dennis Tasa

PEARSON

Senior Meteorology Editor: Christian Botting
Executive Marketing Manager: Neena Bali
Program Manager: Anton Yakovlev
Project Manager: Crissy Dudonis
Editorial Assistant: Amy De Genaro
Director of Development: Jennifer Hart
Development Editor: Veronica Jurgena
Senior Project Manager, Text and Images: Rachel Youdelman
Text Permissions Specialist: Tom Wilcox, Lumina Datamatics
Program Management Team Lead: Kristen Flathman
Project Management Team Lead: David Zielonka
Production Management/Composition: Heidi Allgair/Cenveo® Publisher Services
Design Manager: Mark Ong
Interior and Cover Designer: Jeanne Calabrese
Photo and Illustration Support: International Mapping
Photo Researcher: Kristin Piljay
Operations Specialist: Maura Zaldivar-Garcia
Cover Photo Credit: Supercell moves across the country near West Point Nebraska. Mike Hollingshead/Corbis

Credits and acknowledgments for materials borrowed from other sources and reproduced, with permission, in this textbook appear on the appropriate page within the text or on p. C-1.

Library of Congress Cataloging-in-Publication Data
Lutgens, Frederick K.
The atmosphere : an introduction to meteorology / Frederick K. Lutgens, Edward J. Tarbuck ; illustrated by Dennis Tasa Pearson. — Thirteenth edition.
pages cm
Includes index.
ISBN 978-0-321-98462-3 — ISBN 0-321-98462-5
1. Atmosphere. 2. Meteorology. 3. Weather. I. Tarbuck, Edward J. II. Title.
QC861.2.L87 2014
551.5—dc23
2014031628
1 2 3 4 5 6 7 8 9 10—**V382**—16 15 14

Student edition ISBN 10: 0-321-98462-5; ISBN 13: 978-0-321-98462-3
Instructor's Review Copy ISBN 10: 0-321-98753-5; ISBN 13: 978-0-321-98753-2

PEARSON

www.pearsonhighered.com

Brief Contents

MasteringMeteorology™ Media

1 Introduction to the Atmosphere

SmartFigures
- 1.18 The Mauna Loa CO_2 Record
- 1.20 The Ozone Hole

Geoscience Animations
- Ozone Depletion

Videos
- Ozone Hole
- Global Carbon Uptake by Plants
- Global Changes in Carbon Dioxide Concentrations

GEODe
- The Importance of Weather
- Weather and Climate
- Composition of the Atmosphere
- Extent of the Atmosphere
- Temperature Structure of the Atmosphere
- In the Lab: Reading Weather Maps
- The Influence of Volcanic Ash

2 Heating Earth's Surface and Atmosphere

SmartFigures
- 2.6 Solstices & Equinoxes
- 2.11 Three Mechanisms of Heat Transfer
- 2.15 Solar Radiation Paths
- 2.22 Three Planets, Three Climates

Geoscience Animations
- Earth-Sun Relations
- Atmospheric Energy Balance

Videos
- Seasonal Changes in Global Snow Cover
- July Global Movie
- January Global Movie
- Global Variations in Insolation Through the Year
- Net Radiation at the Top of the Atmosphere
- Solar Eclipse
- Tour of the Electromagnetic Spectrum
- The Sun in Ultraviolet
- Solar Power

GEODe
- Understanding Seasons, Part 1
- Understanding Seasons, Part 2
- Solar Radiation
- What Happens to Incoming Solar Radiation
- The Greenhouse Effect
- In the Lab: The Influence of Color on Albedo

3 Temperature

SmartFigures
- 3.2 Isotherm Maps
- 3.5 Maritime Temperatures
- 3.14 Cloudy vs. Clear Days
- 3.18 January vs. July

Geoscience Animations
- The Gulf Stream
- Ocean Circulation Patterns

Videos
- Global Sea-Surf Temperatures—Climatology
- Seasonal Changes in Land Surface Temperatures
- Heavy Convection over Florida
- Urban Heat Islands
- Temperatures and Agriculture

GEODe
- Basic Temperature Data
- Controls of Temperature

4 Moisture and Atmospheric Stability

SmartFigures
- 4.1 The Water Cycle
- 4.3 Changes of State in Water
- 4.13 Dew Point
- 4.20 Frontal Wedging and Convergence
- 4.24 Atmospheric Stability

Geoscience Animations
- Earth's Water and Hydrologic Cycle
- Water Phase Changes
- Atmospheric Stability

Videos
- Hydrologic Cycle
- Global Evaporation Rates
- January Water Vapor
- July Water Vapor
- Forecasting Relative Humidity
- Gravity Wave Clouds

GEODe
- Water's Changes of State
- Humidity: Water Vapor in the Air
- The Basics of Cloud Formation: Adiabatic Cooling
- Processes That Lift Air
- The Critical Weathermaker: Atmospheric Stability
- In the Lab: Atmospheric Stability

5 Forms of Condensation and Precipitation

SmartFigures
- 5.1 Types of Clouds
- 5.12 Fog
- 5.22 Hail

Videos
- Identifying Clouds in Satellite Imagery
- Clouds Developing Over Florida
- Is That a Cloud?
- Clouds and Aviation
- A Satellite View of Fog
- The Importance of Wind Resistance
- Global Precipitation
- Record-Breaking Hailstorm as Seen by Radar
- Earth Observatory-Global Maps

MapMaster
- Days with Heavy Fog

GEODe
- Classifying Clouds
- Types of Fog
- How Precipitation Forms
- Forms of Precipitation

6 Air Pressure and Winds

SmartFigures
- 6.2 Air Pressure
- 6.14 The Coriolis Effect

Geoscience Animations
- The Coriolis Effect
- Wind Pattern Development
- Cyclones and Anticyclones

Videos
- The Coroliolis Effect on a Merry-Go-Round
- Winds During a Drought
- Hurricane Winds
- The Growth of Wind Power in the U.S.
- Forecasting Wind Patterns

GEODe
- Measuring Air Pressure
- Factors Affecting Wind
- Highs and Lows

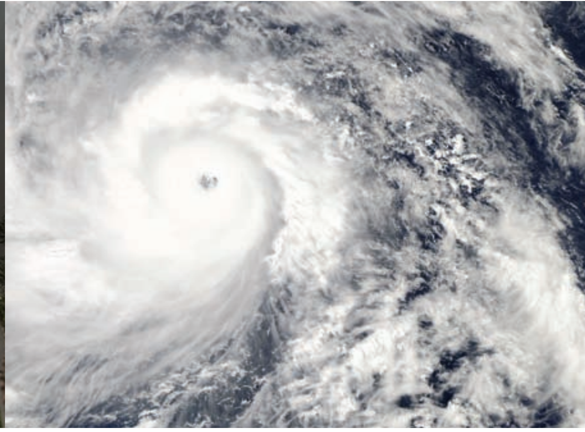
7 Circulation of the Atmosphere

SmartFigures
- 7.2 Local Winds

Contents













Preface

The thirteenth edition of *The Atmosphere* is a college-level text for students taking their first and perhaps only course in meteorology. The text is intended to be a meaningful, nontechnical survey of atmospheric phenomena and weather forecasting to help students understand a field that impacts their daily lives. Our goal is for *The Atmosphere* to provide students with an informative, current, highly readable, text that is an engaging and usable tool for learning the basic principles and concepts of meteorology.

New to This Edition

The 13th edition represents perhaps the *most extensive and thorough revision* in the long history of this textbook.

- **MasteringMeteorology™** 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. Assignable activities in MasteringMeteorology include GIS-inspired *MapMaster Interactive Maps*, *Encounter Meteorology* Explorations using Google Earth™, *SmartFigure* activities, *GeoTutor*s on the most challenging topics in the geosciences, *Geoscience Animations*, *GEODe* tutorials, and more. MasteringMeteorology also includes all instructor resources and a robust Study Area with resources for students.
- **What's Your Forecast?** This new active-learning feature provides students with hands-on forecasting-themed activities. Prepared by experts in different areas of meteorology and climatology, each *What's Your Forecast?* feature highlights the relevance of meteorology in today's world by allowing students to make predictions based on real-world data. Examples of topics include using maps to identify precipitation patterns (Chapter 5), constructing and analyzing a surface weather map (Chapter 9), and predicting the probability of severe storm occurrences (Chapter 10). Critical thinking skills are reinforced as students apply concepts presented in the chapter.
- **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 MasteringMeteorology and teachers can assign them with automatically-graded quizzes.
- **Integrated Mobile Media.** 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. These media are also available in the Study Area of MasteringMeteorology. Including SmartFigures, there are over 130 mobile media items linked to the 13th edition.
- **New and expanded active learning path.** *The Atmosphere*, 13th edition, is designed for learning. Every chapter begins with *Focus on Concepts*, which are numbered learning objectives that correspond to each major section in the chapter. The statements identify the knowledge and skills students should master by the end of the chapter, helping students prioritize key concepts. Within the chapter, each major section is also numbered and restates the relevant learning objective. Each section concludes with *Concept Checks* that allow students to check their understanding and comprehension of important ideas and terms before moving on to the next section. A new end-of-chapter feature, *Concepts in Review*, coordinates with the *Focus on Concepts* at the beginning of the chapter and with the numbered chapter sections. It is a readable, concise overview of key points and terms that often includes photos, diagrams, and questions to help students focus on important ideas and test their understanding of key concepts. Each chapter concludes with *Give It Some Thought*, a series of questions with illustrations that challenge learners with activities that require higher-order thinking skills, such as application, analysis, and synthesis of material in the chapter.
- **An unparalleled visual program.** In addition to the large number of new, high-quality photos and satellite images—many of which highlight recent weather events—dozens of figures are new or have been redrawn by renowned geoscience illustrator, Dennis Tasa. Maps and diagrams are frequently paired with photographs for greater effectiveness. Further, several new tables summarize key phenomena, and many new and revised figures have additional labels that narrate the process being illustrated to guide students as they examine the figures, resulting in a visual program that is clear and easy to understand.

- **Significant updating and revision of 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. Many discussions, case studies, and examples have been updated and revised, including:
  - An expanded discussion of greenhouse gases in Chapter 2
  - An updated discussion of El Niño/La Niña in Chapter 7
  - The extreme cold of the 2013/2014 U.S. Midwest winter (with new figure) integrated into the discussion of air mass movement in Chapter 8
  - The linkage between thunderstorms and climate change introduced in Chapter 10
  - Several new figures and a new *Severe and Hazardous Weather* box in Chapter 11 featuring 2013 Super Typhoon Haiyan
  - Chapter 12 has been expanded and rewritten to feature recent forecasting techniques and includes a new section, "The Role of the Forecaster," and a new box, "Thermodynamic Diagrams"
  - Chapter 14 presents key findings from the IPCC 5th Assessment report *Climate Change 2013: The Physical Science Basis*
  - Discussion of climate change and its possible impacts on weather and climate can be found throughout the book

Distinguishing Features

Readability

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 13th edition, we have continued to improve readability by examining chapter organization and flow and by writing in a more personal style. Significant portions of several chapters were substantially rewritten in an effort to make the material easier to understand. For example, Chapter 1 was shortened and reorganized to improve flow and focus on key themes; Chapters 3, 4, and 6 have fewer main sections, but subsections were revised with more descriptive subheadings to help students understand linkages among phenomena. The order of main sections was changed for Chapters 9 and 12 to improve presentation of key concepts, and Chapter 12 was completely updated and rewritten to reflect new technologies in weather forecasting.

Focus on Basic Principles and Instructor Flexibility

Although many topical issues are addressed in the 13th 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 13th edition continues to include these important learning aids:

- *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. Instructors can discuss these in class or assign the questions to students from the book or MasteringMeteorology. Many of these have been updated with recent photos, and several chapters include new topics.
- Every chapter includes several *Students Sometimes Ask* features. Instructors and students continue to react favorably and indicate that the questions and answers that are 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 (10, "Thunderstorms and Tornadoes," and 11, "Hurricanes") that focus entirely on such topics, 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 one or two active-learning questions to help students test their understanding and link these events to critical chapter concepts.
- In many chapters, *Problems,* many with quantitative orientation, are included. Most problems require only basic math skills and allow students to enhance their understanding by applying concepts and principles explained in the chapter.

Acknowledgments

Writing a college textbook requires the talents and cooperation of many people. It is truly a team effort, and the authors are fortunate to be part of an extraordinary team at Pearson Education. In addition to being great people to work with, all are committed to producing the best textbooks possible. Special thanks to our senior editor, Christian Botting, who invested a great deal of time, energy, and effort in this project. We appreciate his enthusiasm, hard work, and quest for excellence. We also appreciate our conscientious project manager, Crissy Dudonis, whose job it was to keep track of all that was going on—and a lot was going on. The 13th edition was certainly improved by the talents of our developmental editor, Veronica Jurgena. Many thanks. It was the job of the production team, led by Heidi Allgair at Cenveo® Publisher Services, to turn our manuscript into a finished product. The team also included copyeditor Kitty Wilson, compositor Annamarie Boley, and photo researcher Kristin Piljay. We think these talented people did great work. All are true professionals, with whom we are very fortunate to be associated.

Working with Dennis Tasa, who is responsible for all of the text's outstanding illustrations, is always special for us. He has been part of our team for more than 30 years. We not only value his artistic talents, hard work, patience, and imagination, but his friendship as well.

Many thanks also go to those colleagues who prepared in-depth reviews. Their critical comments and thoughtful input helped guide our work and clearly strengthened the text. Special thanks to:

Jason Allard, Valdosta State University
Mark Anderson, University of Nebraska–Lincoln
Deanna Bergondo, U.S. Coast Guard Academy
Anne Case Hanks, University of Louisiana–Monroe
William Conant, University of Arizona
Nathaniel Cunningham, Nebraska Wesleyan University
Kerry Doyle, Southern Illinois University–Edwardsville
Ron Dowey, Harrisburg Area Community College–Harrisburg
Douglas Gamble, University of North Carolina, Wilmington
Greg Gaston, University of North Alabama
Redina Herman, Western Illinois University
Mark Hildebrand, Southern Illinois University–Edwardsville
Helenmary Hotz, University of Massachusetts–Boston
Brennan Jordan, University of South Dakota
Timothy and Jennifer Klingler, Delta College
Mark Lemmon, Texas A&M University
Robert Mania, Kentucky State University
Jason Ortegren, University of West Florida
Robert Quinn, Eastern Washington University
Robert S. Rose, Tidewater Community College–Virginia Beach
Marshall Shepherd, University of Georgia
Roger D. Shew, University of North Carolina–Wilmington
Steve Simpson, Highland Community College
Eric Snodgrass, University of Illinois–Urbana-Champaign
Andrew Van Tuyl, Galivan College
Chuck Weidman, University of Arizona
Henry J. Zintambila, Illinois State University

We are very grateful to Neva Duncan-Tabb (St. Petersburg College), who authored the *Instructor Resource Manual,* to Jennifer Johnson (Ferris State University) for writing the *Test Bank,* and to the following expert contributors who have written the special *What's Your Forecast?* features throughout the book: Redina Herman (Western Illinois University), Marshall Shepherd (University of Georgia), Harold Brooks (NOAA National Severe Storms Laboratory), Brian McNoldy (University of Miami), Adam Clark (NOAA National Severe Storms Laboratory), and Donald Wuebbles (University of Illinois at Urbana-Champaign).

Last, but certainly not least, we gratefully acknowledge the support and encouragement of our wives, Nancy Lutgens and Joanne Bannon. Preparation of *The Atmosphere*, 13th edition, would have been far more difficult without their patience and understanding.

Fred Lutgens

Ed Tarbuck

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.

Along with developing and exploring digital solutions to our market's needs, Pearson has a strong commitment to achieving carbon-neutrality. As of 2009, Pearson became the first carbon- and climate-neutral publishing company. Since then, Pearson has remained strongly committed to measuring, reducing, and offsetting our carbon footprint.

The future holds great promise for reducing our impact on Earth's environment, and Pearson is proud to be leading the way. We strive to publish the best books with the most up-to-date and accurate content, and to do so in ways that minimize our impact on Earth. To learn more about our initiatives, please visit **www.pearson.com/social-impact.html**

Digital & Print Resources

For Students & Teachers

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, that focus on course objectives, and that 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 GIS-inspired MapMaster™ interactive maps, Encounter Meteorology Google Earth Explorations, Videos, Geoscience Animations, Map Projection Tutorials, GeoTutor coaching activities on the toughest topics in the geosciences, GEODe Tutorials, 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, an optional Pearson eText, and more.

Pearson eText gives students access to the text whenever and wherever they can access the Internet. Features of Pearson eText include:

- Now available on smartphones and tablets.
- Seamlessly integrated videos and other rich media.
- Fully accessible (screen-reader ready).
- Configurable reading settings, including resizable type and night reading mode.
- Instructor and student note-taking, highlighting, bookmarking, and search.

www.masteringmeteorology.com.

- ***Geoscience Animation Library on DVD,* 5th Edition [0321716841]** Geoscience Animations illuminate many difficult-to-visualize concepts. 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.

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 MasteringMeteorology, 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. The 23rd edition includes 160 pages of digitally produced reference maps, as well as thematic maps on 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 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. But the sheer volume of scientific data remains inscrutable to the general public. In just over 200 pages, this practical text presents and expands on the essential findings of the IPCC's 5th Assessment Report 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.

- ***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, a corresponding Google Earth KMZ file, and online quizzes whose results can be e-mailed to teachers.

For Teachers

Learning Catalytics is a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics, you can:

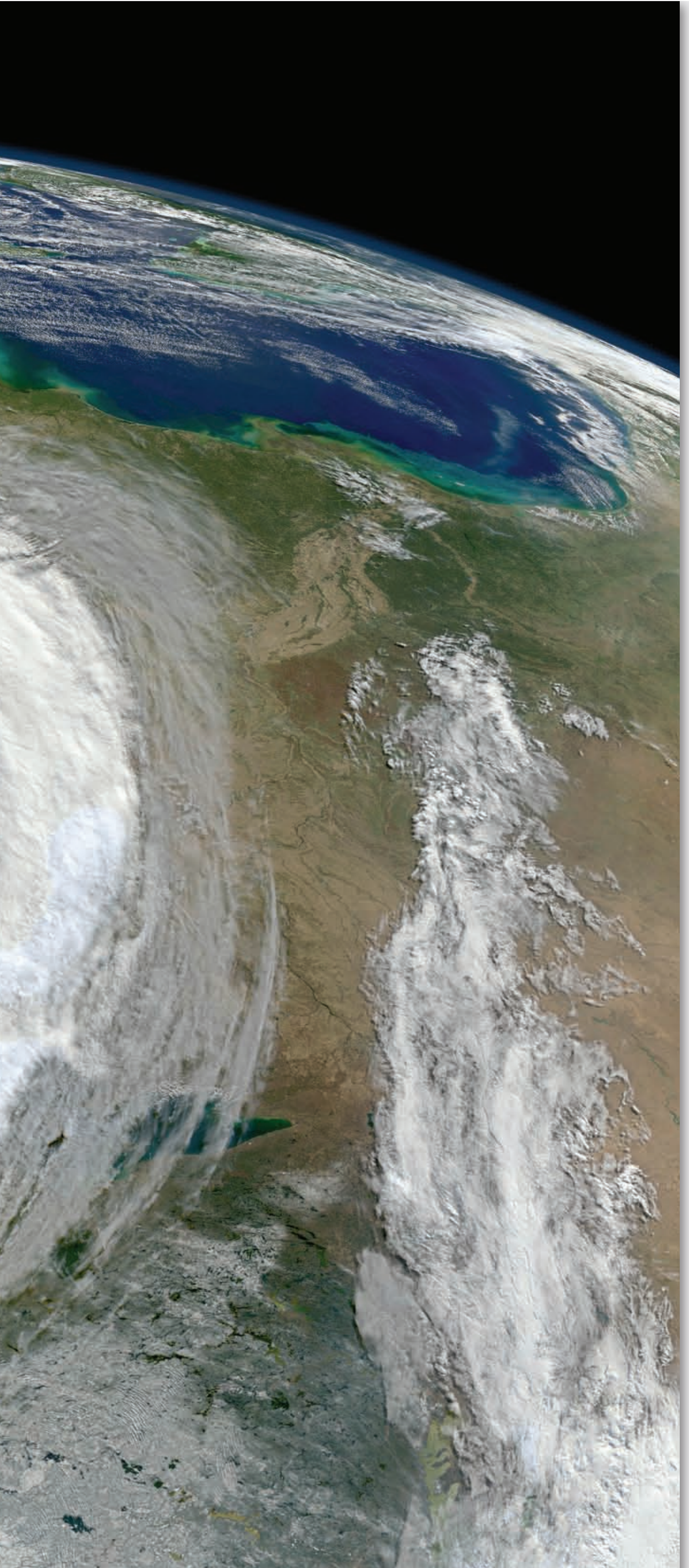
- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

Learning Catalytics is a technology that has grown out of 20 years of cutting-edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with MasteringMeteorology.

- ***Instructor Resource Manual* (download only) by Neva Duncan-Tabb, St. Petersburg College [0321987640]** The *Instructor Resource Manual* is intended as a resource for both new and experienced instructors. It includes a variety of lecture outlines, teaching tips, advice about how to integrate visual supplements (including the MasteringMeteorology resources), answers to the textbook chapter questions, and various other ideas for the classroom.
  See www.pearsonhighered.com/irc.
- **TestGen® Computerized *Test Bank* (download only) by Jennifer Johnson, Ferris State University [0321987683]** 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* [0321987659]** 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 IRDVD includes:
  - All textbook images as JPEGs, PDFs, and PowerPoint™ presentations
  - Pre-authored Lecture Outline PowerPoint™ presentations, which outline the concepts of each chapter with embedded art and can be customized to fit teachers' lecture requirements
  - "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.

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:

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

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

1.3 List and describe Earth's four major spheres. Define *system* and explain why Earth is considered to be a system.

1.4 List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically. Explain why ozone depletion is a significant global issue.

1.5 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.

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 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.

MM GEODe ▶ Introduction to the Atmosphere ▶ Weather and Climate

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

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 that are far from the influence of the ocean. Some landscapes are mountainous, and others are dominated by plains. It is a place where Pacific storms strike the west coast, while the eastern states are sometimes influenced by events in the Atlantic and the Gulf of Mexico. For those in the center of the country, it is common to experience weather events triggered when frigid southward-bound Canadian air masses clash with northward-moving tropical air masses from the Gulf of Mexico.

Stories about weather are a routine part of the daily news. Articles and items about the effects of heat, cold, floods, drought, fog, snow, ice, and strong winds are commonplace (**Fig. 1.1**). Memorable weather events occur everywhere on our planet. 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. Beyond its direct impact on the lives of individuals, the weather has a strong effect on the world economy, by influencing agriculture, energy use, water resources, transportation, and industry.

Weather influences our lives a great deal. Yet it is also important to realize that people influence the atmosphere and its behavior as well (**Fig. 1.2**). There are, and will continue to be, significant economic, political, and scientific decisions to

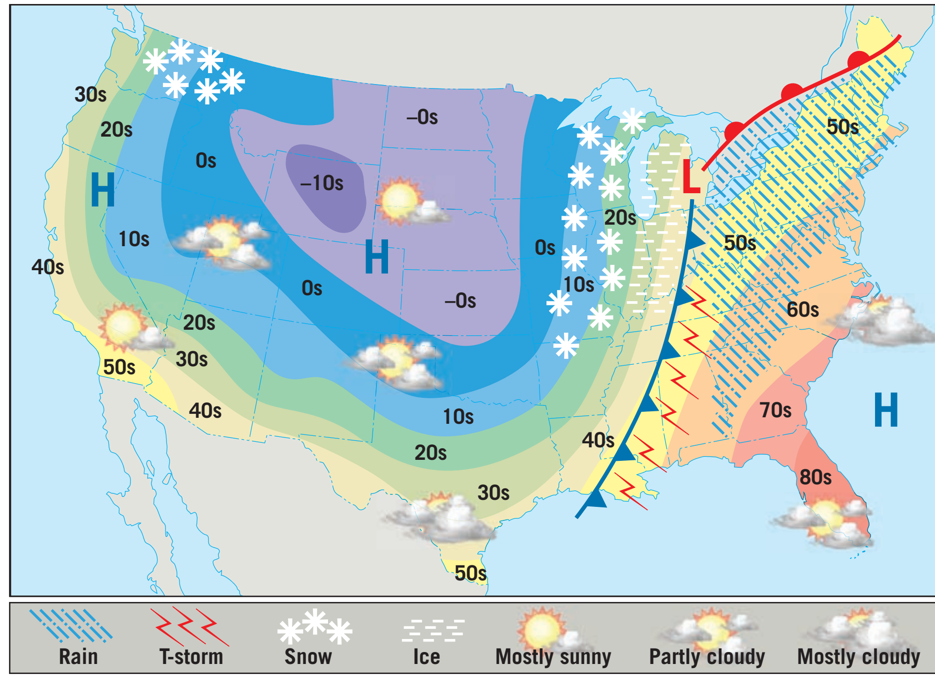
▼ **Figure 1.1 An extraordinary winter** The winter of 2013–2014 brought record-breaking cold and snow to much of the eastern half of the conterminous United States. Meanwhile, Alaska and much of the West were much warmer and drier than usual.

▲ **Figure 1.2 People influence the atmosphere** Smoke bellows from a coal-fired electricity generating plant in New Delhi, India, in June 2008. In addition to smoke, this power plant also emits gases such as sulfur dioxide and carbon dioxide that contribute to air pollution and global climate change.

make involving these impacts. Dealing with the effects of and controlling air pollution is one example. 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.

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*. Along with geology, oceanography, and astronomy, meteorology is considered one of the *Earth sciences*—the sciences that seek to understand our planet. It is important to point out that there are not strict boundaries among the Earth sciences; in many situations, these sciences overlap. Moreover, all the Earth sciences involve an understanding and application of knowledge and principles from physics, chemistry, and biology. You will see many examples of this overlap in your study of meteorology.



▲ **Figure 1.3 Newspaper weather map** A typical newspaper weather map for a day in late December. The color bands show predicted high temperatures for the day.

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 is constantly changing, sometimes from hour to hour and at other times from day to day. It is a term that refers to the state of the atmosphere at a given time and place. 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 is an inadequate definition. In order to accurately portray the character of an area, variations and extremes must also be included, as well as the probabilities that such departures will take place. For example, it is necessary for farmers to know the average rainfall during the growing season, and it is also important to know the frequency of extremely wet and extremely dry years. Thus, climate is the sum of all statistical weather information that helps describe a place or region.

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

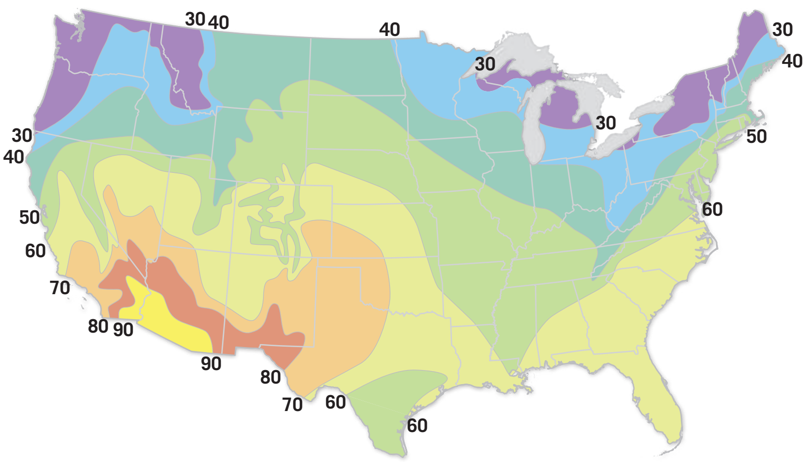
Suppose you were planning a vacation trip to an unfamiliar place. You would probably want to know what kind of weather to expect. Such information would help as you selected clothes to pack and could influence decisions regarding activities you might engage in during your stay. Unfortunately, weather 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 map in Figure 1.4 shows the average percentage of possible sunshine in the United States for the month of November, and the graph in Figure 1.5 shows average daily high and low temperatures for each month, as well as extremes, for New York City.

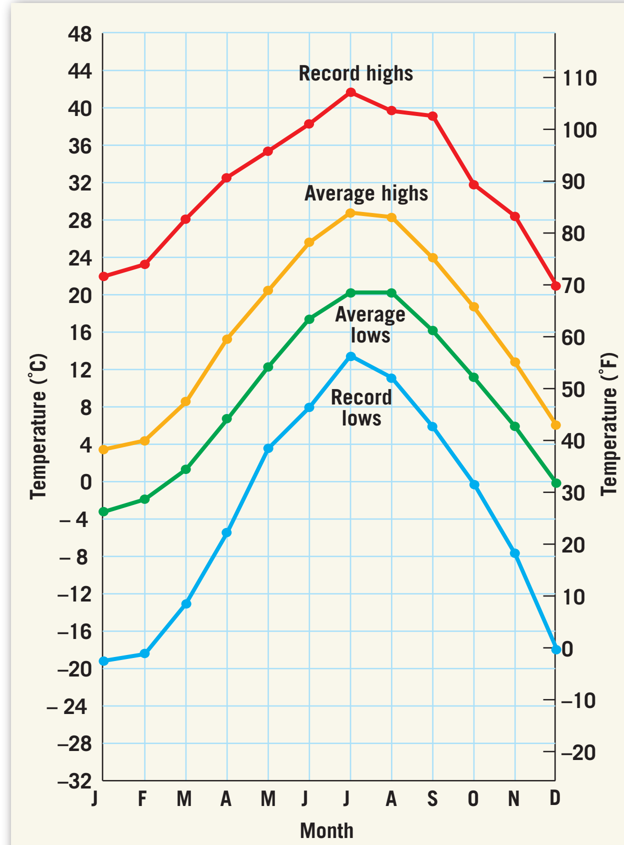
students sometimes ask...

Does meteorology have anything to do with meteors?

There is a connection. The word *meteor* refers to solid particles (meteoroids) that enter Earth's atmosphere from space and "burn up" due to friction ("shooting stars"). The term *meteorology* was coined in 340 B.C., 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 we distinguish between particles of ice or water in the atmosphere (*hydrometeors*) and extraterrestrial objects (meteoroids, or meteors).



▲ **Figure 1.4 November sunshine** Mean percentage of possible sunshine for November for the contiguous 48 states. Southern Arizona is clearly the sunniest area. By contrast, parts of the Pacific Northwest receive a much smaller percentage of the possible sunshine. Climate maps such as this one are based on many years of data.



▲ **Figure 1.5 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. It shows that there can be significant departures from the average.

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 actually experience cool, overcast, and rainy weather. There is a well-known saying that summarizes this idea: "Climate is what you expect, but weather is what you get."

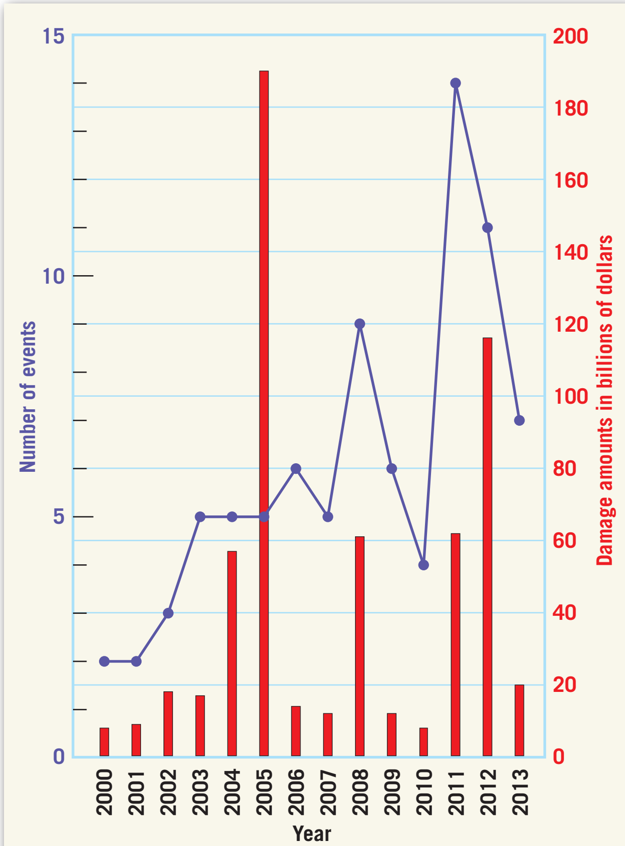
The nature of both weather and climate is expressed in terms of the same basic **elements**—quantities or properties that are measured regularly. The most important are (1) the *temperature* of the air, (2) the *humidity* of the air, (3) the type and amount of *cloudiness,* (4) the type and amount of *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. 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: Assault by the Elements

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

For most people, occurrences of severe weather 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 image of Hurricane Sandy and the tornado damage depicted in Figure 1.6 are good examples.

▼ **Figure 1.6 Late season tornado** Although "tornado season" in central Illinois is spring and summer, a devastating tornado struck Washington, Illinois, on November 17, 2013. With maximum winds of 306 kilometers (190 miles) per hour, the storm caused complete destruction of well-built homes.



▲ **Figure 1.7 Billion-dollar weather events** Between 2000 and 2013, the United States experienced 84 weather-related disasters in which overall damages and costs reached or exceeded $1 billion. The line graph shows the number of events that occurred each year, and the bar graph shows damage amounts in billions of dollars (normalized to 2013 dollars). The total losses for the 84 events exceeded $600 billion! (Data from NOAA)

Of course, other atmospheric hazards 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. Moreover, although severe storms and floods usually generate more attention, droughts can be just as devastating and carry an even bigger price tag.

Between 2000 and 2013, the United States experienced 84 weather-related disasters in which overall damages and costs reached or exceeded $1 billion (Fig. 1.7). In addition to taking more than 4200 lives, the combined economic costs of these events exceeded $600 billion!

At appropriate places throughout this book, you will have an opportunity to learn about atmospheric hazards. Two entire chapters (Chapter 10 and Chapter 11) focus almost entirely on hazardous weather. In addition, a number of the book's special-interest boxes are devoted to a broad variety of severe and hazardous weather, including heat waves, winter storms, floods, dust storms, drought, mudflows, and lightning. 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.

✓ Concept Checks 1.1

1. Define and distinguish among meteorology, weather, and climate.
2. List the basic elements of weather and climate.
3. List at least 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.

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. Developing an understanding of how science is done and how scientists work is an important theme in this book. You will explore the difficulties of gathering data and learn some of the ingenious methods that have been developed to overcome these difficulties. You will also see examples of how hypotheses are formulated and tested, as well as learn about the development of some significant scientific theories.

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 processes and conditions that produce certain cloud types, meteorologists are often able to predict the approximate time and place of their formation.

The development of new scientific knowledge involves some basic logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect scientific data through observation and measurement. The types of data that are collected often seek to answer a well-defined question about the natural world, such as "Why does fog frequently develop in this place?" or "What causes rain to form in this cloud type?" Because some error is inevitable, the accuracy of a particular measurement or observation is always open to question. Nevertheless, these data are essential to science and serve as a springboard for the development of scientific theories (Box 1.1).

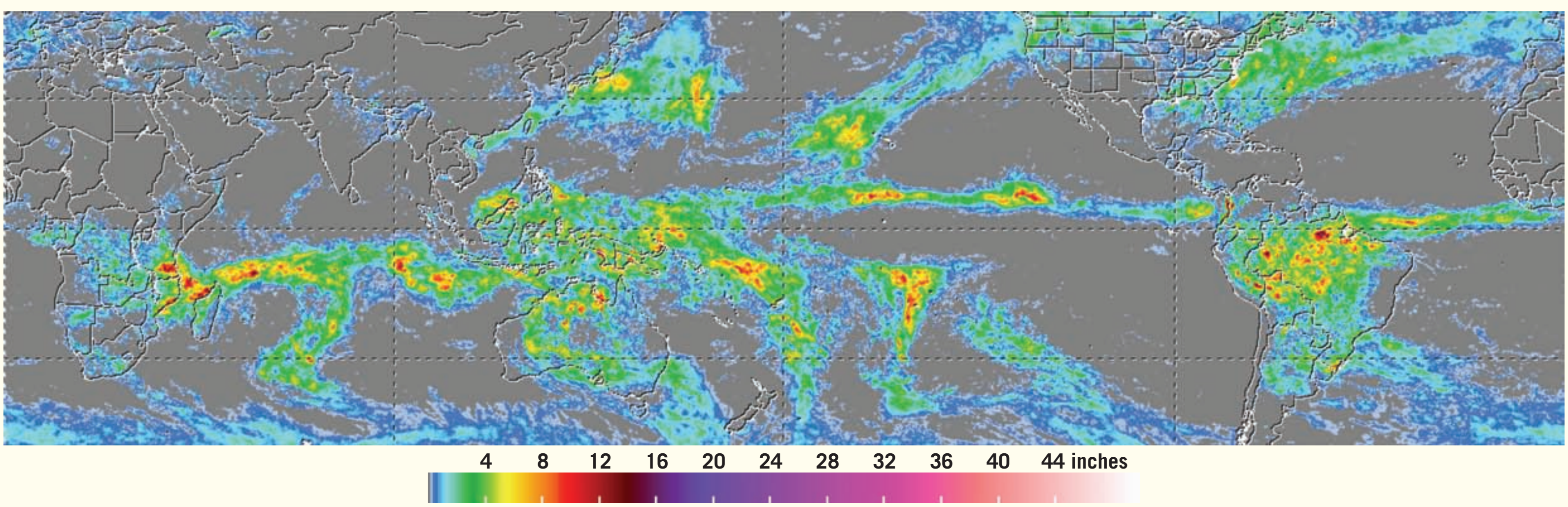
Box 1.1 Monitoring Earth from Space

Scientific data are gathered in many ways, including through laboratory experiments and field observations and measurements. Satellites provide another very important source of data. Satellite images give us perspectives that are difficult to gain from more traditional sources. The chapter-opening image of Hurricane Sandy is a good example. Moreover, the high-tech instruments aboard many satellites enable scientists to gather information from remote regions where data are otherwise scarce.

The image in **Figure 1.A** is from NASA's *Tropical Rainfall Measuring Mission* (*TRMM*). *TRMM* is a research satellite designed to expand our understanding of Earth's water (hydrologic) cycle and its role in our climate system. By covering the region between the latitudes 36° north and 36° south, it provides much-needed data on rainfall and the heat release associated with rainfall. Many types of measurements and images are possible. Instruments aboard the *TRMM* satellite have greatly expanded our ability to collect precipitation data. In addition to recording data for land areas, this satellite provides extremely precise measurements of rainfall over the oceans, where conventional land-based instruments cannot reach. This is especially important because much of Earth's rain falls in ocean-covered tropical areas, and a great deal of the globe's weather-producing energy comes from heat exchanges involved in the rainfall process. Before the launch of the *TRMM* satellite, information on the intensity and amount of rainfall over the tropics was sparse. Such data are crucial to understanding and predicting global climate change.

Questions

1. Examine the map in Figure 1.A. During the time span represented, approximately what is the highest rainfall total on the map?
2. What are some advantages that satellites provide in terms of gathering information about Earth? Support your answer with an example from Figure 1.A.



▲ **Figure 1.A Monitoring rainfall** This map shows rainfall for a 7-day period in February 2014. It was constructed using *TRMM* data.

Hypothesis

Once data have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happen in the manner observed. They often do this by constructing a tentative (or untested) explanation, which is called a scientific **hypothesis**. It is best if an investigator can formulate more than one hypothesis to explain a given set of observations. If an individual scientist is unable to devise multiple hypotheses, others in the scientific community will almost always develop alternative explanations. A spirited debate frequently ensues. As a result, proponents of opposing hypotheses conduct extensive research, and scientific journals make the results available to the wider scientific community.

Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. If a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it may seem. The verification process requires that *predictions* be made based on the hypothesis being considered and that these predictions be tested by being compared against objective observations of nature. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are ultimately 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.

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

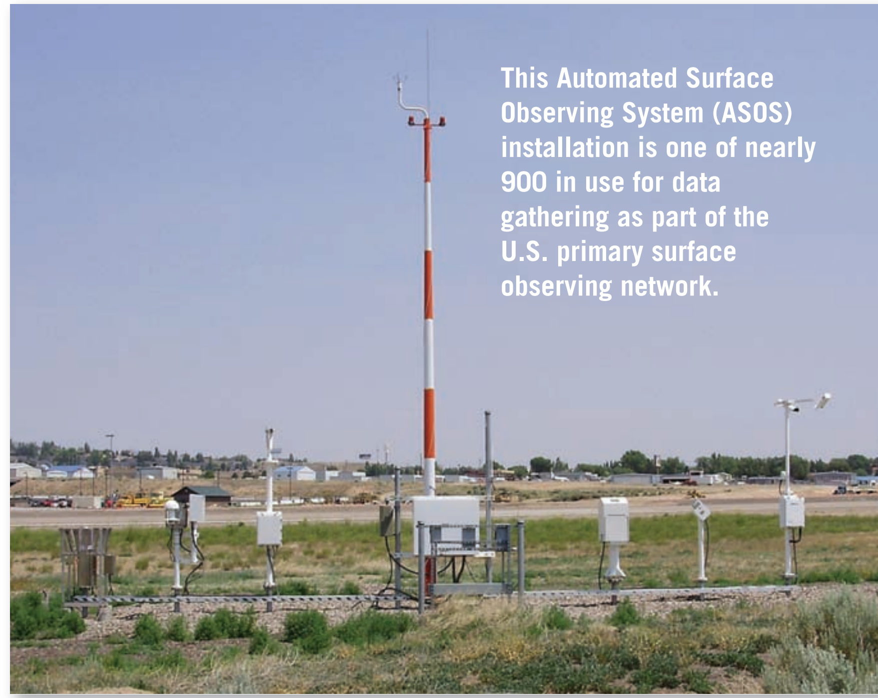
Some theories that are extensively documented and extremely well supported are comprehensive in scope. An example from the Earth sciences is the theory of plate tectonics, which provides the framework for understanding the origin of mountains, earthquakes, and volcanic activity. It also explains the 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.

Scientific Methods

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."*

There is no fixed path for scientists that leads unerringly to scientific knowledge. Nevertheless, many scientific investigations involve the following:

- A question is raised about the natural world.
- Scientific data that relate to the question are collected (Fig. 1.8).
- Questions that relate to the data are posed, and one or more working hypotheses are developed that may answer these questions.
- Observations, experiments, and models are developed to test the hypotheses.



▲ **Figure 1.8 Observation and measurement** Gathering data and making careful observations are basic parts of scientific inquiry.

- 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 may 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 when dealing with natural processes that occur on very long time scales or take place in extreme or inaccessible locations. Still other scientific advancements have been made when a totally unexpected happening occurred 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."**

students sometimes ask...

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.

*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" by Everett Mendelsohn, Garland E. Allen, Roy M. MacLeod, Springer 2001.