



ESSENTIALS OF METEOROLOGY

An Invitation to the Atmosphere

EIGHTH EDITION

C. Donald Ahrens
Robert Henson

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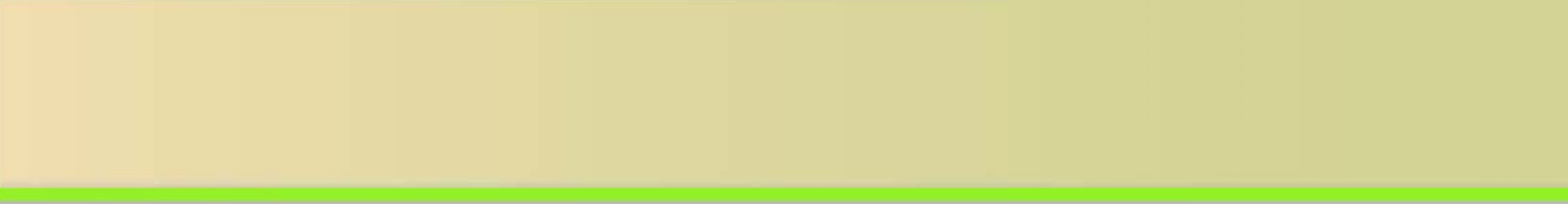
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ESSENTIALS OF METEOROLOGY



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Essentials of Meteorology

AN INVITATION TO THE ATMOSPHERE

C. Donald Ahrens
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Essentials of Meteorology
An Invitation to the Atmosphere

Eighth Edition

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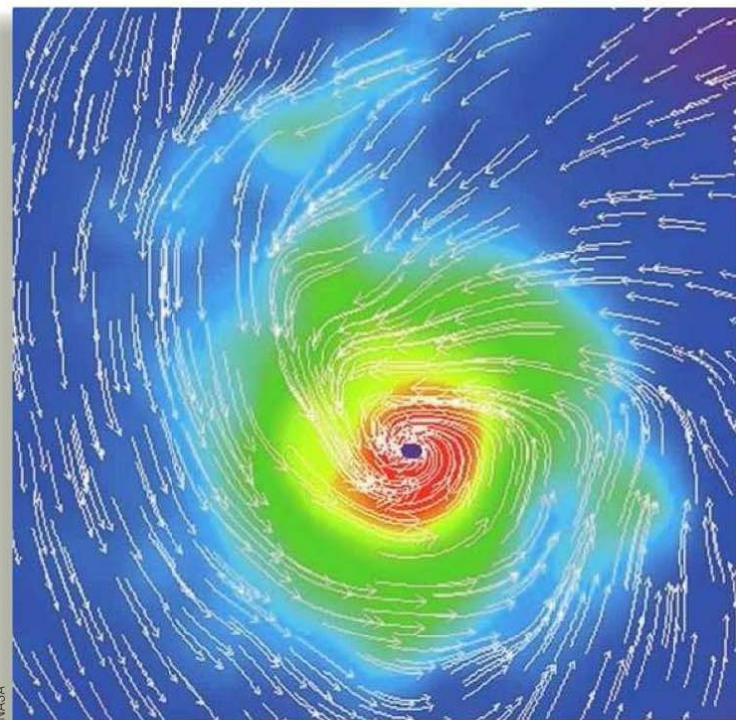
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PREFACE

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

In recent years, weather and climate have become front page news, from record-setting extreme weather events to environmental issues such as global warming and ozone depletion. The dynamic nature of the atmosphere seems to demand our attention and understanding more these days than ever before. Almost daily, there are newspaper articles describing some weather event or impending climate change. For this reason, and the fact that weather influences our daily lives in so many ways, interest in meteorology (the study of the atmosphere) has been growing. This rapidly developing and popular science is giving us more information about the workings of the atmosphere than ever before. One of the reasons that meteorology is such an engaging science to study is that the atmosphere is a universally accessible laboratory for everyone. Although the atmosphere will always provide challenges for us, as research and technology advance, our ability to understand our atmosphere improves as well. The information available to you in this book, therefore, is intended to aid in your own personal understanding and appreciation of our Earth's dynamic atmosphere.

About This Book

Essentials of Meteorology is written for students taking an introductory course on the atmospheric environment. The main purpose of the text is to convey meteorological concepts in a visual, practical, and nonmathematical manner. In addition, the intent of the book is to stimulate curiosity in the reader and to answer questions about weather and climate that arise in our day-to-day lives. Although introductory in nature, this eighth edition maintains scientific integrity and includes up-to-date information on large-scale topics, such as global warming, ozone depletion, and El Niño, as well as discussion of recent high-profile weather events. As in previous editions, no special prerequisites are necessary for understanding.

Written expressly for the student, this book emphasizes the understanding and application of meteorological principles. The text encourages watching the weather so that it becomes “alive,” allowing readers to immediately apply textbook material to the world around them. To assist with this endeavor, a color Cloud Chart appears at the back of the text. The Cloud Chart can be separated from the book and used as a learning tool at any place one chooses to observe the sky. To strengthen points and clarify concepts, illustrations are rendered in full color throughout. Color photographs were carefully selected to illustrate features, stimulate interest, and show how exciting the study of weather can be. To enhance the value of the book, several appendices that were only available online in the seventh edition have been reincorporated.

Organized into fifteen chapters, *Essentials of Meteorology* is designed to provide maximum flexibility to instructors of weather and climate courses. Thus, chapters can be covered in any desired order. For example, Chapter 15, “Light, Color, and Atmospheric Optics,” is self-contained and can be covered earlier if so desired. Instructors, then, are able to tailor this text to their particular needs. This book basically follows a traditional approach. After an introductory chapter on the origin, composition, and structure of the atmosphere, it covers solar energy, air temperature, humidity, clouds, precipitation, and winds. Then comes a chapter on air masses, fronts, and middle-latitude cyclonic storms. Weather prediction and severe storms are next. A chapter on hurricanes is followed by a chapter on global climate. A chapter on climate change is next. A chapter on air pollution precedes the final chapter on atmospheric optics.

Each chapter contains at least two Focus sections, which either expand on material in the main text or explore a subject closely related to what is being discussed. Focus sections fall into one of three distinct categories: Observations, Special Topics, and Environmental Issues. Some include material that is not always found in introductory meteorology textbooks—subjects such as space weather, the scientific method, and wind energy. Others help to bridge theory and practice. This edition contains several new or rewritten Focus sections, including an updated discussion of nor'easters in Chapter 8 and a new Focus section on tornado damage patterns in Chapter 10.

Set apart as “Did You Know?” features in each chapter is weather information that may not be commonly

known, yet pertains to the topic under discussion. Designed to bring the reader into the text, most of these weather highlights relate to some interesting weather fact or astonishing event.

Each chapter incorporates other effective learning aids:

- A major topic outline begins each chapter.
- Interesting introductory pieces draw the reader naturally into the main text.
- Important terms are boldfaced, with their definitions appearing in the glossary or in the text.
- Key phrases are italicized.
- English equivalents of metric units are immediately provided in parentheses.
- A brief review of the main points is placed toward the middle of most chapters.
- Each chapter ends with a summary of the main ideas.
- A list of key terms with page references follows each chapter, allowing students to review and reinforce their knowledge of key concepts.
- Questions for Review act to check how well students assimilate the material.
- Questions for Thought and Exploration encourage students to synthesize learned concepts for deeper understanding.
- References to 19 concept animations are compiled on pp. xx-xxi. These animations convey an immediate appreciation of how a process works and help students visualize the more difficult concepts in meteorology. Animations can be found on the Meteorology CourseMate, accessed through Cengagebrain.com.
- At the end of each chapter are questions that relate to articles found on the Global Geoscience Watch website, available on its own or via the Meteorology CourseMate.

Eight appendices conclude the book. In addition, at the end of the book, a compilation of supplementary reading material is presented, as is an extensive glossary. On the endsheet at the back of the book is a geophysical map of North America. The map serves as a quick reference for locating states, provinces, and geographical features, such as mountain ranges and large bodies of water.

Supplemental Material and Technology Support

TECHNOLOGY FOR THE INSTRUCTOR

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

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

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Global Geoscience Watch Updated several times a day, the Global Geoscience Watch is a focused portal into GREENR—our Global Reference on the Environment, Energy, and Natural Resources—an ideal one-stop site for classroom discussion and research projects for all things geoscience! Broken into the four key course areas (Geography, Geology, Meteorology, and Oceanography), you can easily get to the most relevant content available for your course. You and your students will have access to the latest information from trusted academic journals, news outlets, and magazines. You also will receive access to statistics, primary sources, case studies, podcasts, and much more!

TECHNOLOGY FOR THE STUDENT

Earth Science MindTap for Essentials of Meteorology MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center website, a course delivery platform, or a Learning Management System. More than 70 percent of students surveyed said that it was unlike anything they have ever seen before. MindTap is a new personal learning experience that combines all of your digital assets—readings, multimedia, activities, study tools, and assessments—into a singular learning path to improve student outcomes.

Lab Manual Developed by the Oklahoma Climatological Survey (OCS) research and service facility, in concert with the University of Oklahoma, *Explorations in Meteorology* places a strong emphasis on helping students understand weather and climate by using real meteorological data. The activities in this lab manual require that students tap into the OCS archives of meteorological data in order to complete meteorological exercises. Full-color pictures and data graphs help students visually understand weather and severe weather topics. The lab manual also challenges students by providing optional questions intended for honors students, making this lab manual appropriate for both introductory and honors meteorology courses.

Eighth Edition Changes

This edition of *Essentials of Meteorology* includes a coauthor—meteorologist and science journalist Robert Henson (Weather Underground). For more than 20 years, Henson produced publications and websites for the University Corporation for Atmospheric Research, which manages the National Center for Atmospheric Research. He is an expert on severe weather, including tornadoes, thunderstorms, and hurricanes. He has also analyzed how television weathercasters cover major storms and report on climate change. Henson is the author of four trade books on meteorology, including *The Thinking Person's Guide to Climate Change* (previously *The Rough Guide to Climate Change*, the first edition of which was shortlisted for the United Kingdom's Royal Society Prize for Science Books).

The authors have carried out extensive updates and revisions to this eighth edition of *Essentials of Meteorology*, reflecting the ever-changing nature of the field and the atmosphere itself. Dozens of new photos and new or revised color illustrations help students visualize the excitement of the atmosphere.

- Chapter 1, “Earth’s Atmosphere,” continues to serve as a broad overview of the atmosphere. The text now begins with a discussion of the scientific method and its importance. To help draw students into the material, the introduction to meteorology and the summary of extreme weather types has been placed earlier in the chapter, followed by discussion of the chemistry and vertical structure of Earth’s atmosphere. Among recent events now included are the severe flooding over the Southern Plains and Southeast in 2015 and the Houston flash flood of April 2016.
- Chapter 2, “Warming and Cooling Earth and Its Atmosphere,” contains up-to-date statistics and background on greenhouse gases and climate change, topics covered in more detail later in the book. Discussion of the potential impact of clouds on future global warming has been updated.
- In Chapter 3, “Air Temperature,” several figures and tables have been updated so that they refer to normals drawn from the most recent reference period (1981–2010).
- Chapter 4, “Humidity, Condensation, and Clouds,” includes updated material on satellite observations, including new background and artwork from the Global Precipitation Mission satellite. Also included is a “Did You Know?” box on the high-impact Atlanta snowstorm of January 2014.
- Chapter 5, “Cloud Development and Precipitation,” includes a new graphic. New satellite observing techniques are also noted and illustrated in this chapter.
- Chapter 6, “Air Pressure and Winds,” includes a substantially enhanced description and revised illustrations of the interplay between the pressure gradient and Coriolis forces in cyclonic and anticyclonic flow. Several other illustrations have been revised for clarity, and the discussion of scatterometers has been updated. A box on wind energy features the most recent data on wind energy adoption.
- Chapter 7, “Atmospheric Circulations,” features a major restructuring, update, and expansion of sections dealing with the El Niño/Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, and Arctic Oscillation, including several new and updated images. The opening section, which introduces scales of atmospheric motion, has also been revised for clarity.
- Chapter 8, “Air Masses, Fronts, and Middle-Latitude Cyclones,” now includes discussion of atmospheric rivers and an illustration of their impacts. In line with recent research, the section on occluded fronts stresses the prevalence of warm-type over cold-type occluded fronts. The discussion of drylines has been expanded, and the Focus box on nor’easters has been reworked to spotlight the record-setting East Coast snowstorm of January 2016.

- “Weather Forecasting” (Chapter 9) has undergone substantial revision, with several updated graphics. Three major types of satellite imagery are introduced near the beginning of the chapter. Explanations of watches, warnings, and forecasts of various durations (including seasonal outlooks) are now incorporated in a new section, “Time Range of Forecasts.” The concept of the forecast funnel is also introduced.
- Chapter 10, “Thunderstorms and Tornadoes,” includes several new and updated illustrations, depicting low- and high-precipitation supercells, a roll cloud, and a shelf cloud. An expanded section covers both flash flooding and river flooding and their connection to thunderstorms, including examples from Colorado (2013) and Texas and Oklahoma (2015). A new Focus box explores the baffling damage patterns that tornadoes can produce. The effort to accommodate new ways of estimating and reporting tornado wind speed (such as mobile radar reports) is also noted.
- The chapter on “Hurricanes” (Chapter 11) includes a new opening section that introduces students to the terrible impacts of Hurricane Katrina. Several graphics that use satellite imagery to explain basic concepts have been updated with recent tropical cyclones. Charts on hurricane climatology have been brought up to date, and an expanded range of both historical and recent examples are discussed, including the Galveston hurricane of 1900, the New England hurricane of 1938, and Typhoon Haiyan from 2013.
- Chapter 12, “Global Climate,” includes a number of updates to climatological charts and discussion, drawing on the most recent set of United States climate normals (1981–2010).
- Chapter 13, “Earth’s Changing Climate,” has been revised throughout to reflect increasing confidence on a variety of climate change indicators and impacts. Also incorporated are graphics, conclusions, and emission pathways from the Fifth Assessment Report (2013–14) of the Intergovernmental Panel on Climate Change. The extremely quiet solar cycle of the late 2000s and early 2010s is noted, along with a variety of weather extremes from recent years that are relevant to climate change. The Paris Accord is discussed in the context of the Kyoto Protocol

that preceded it. A number of diagrams have been updated.

- The chapter on “Air Pollution” (Chapter 14) has been revised to include the latest air pollution trends across the United States as well as the latest information on ozone depletion in the Arctic and Antarctic. The U.S. Clean Power Plan is introduced, and the devastating impacts of both indoor and outdoor air pollution are discussed, including the effects of tiny particulates on cardiovascular health.
- Several of the photos in Chapter 15, “Light, Color, and Atmospheric Optics,” have been replaced with spectacular new examples (e.g., anticrepuscular rays and double rainbows).

Acknowledgments

Many people have contributed to the eighth edition of *Essentials of Meteorology*. A very special and most grateful thank-you goes to Lita Ahrens who proofread each chapter. Special thank you to Charles Preppernau for rendering the beautiful art and to Janet Hansen for careful proofreading.

We are indebted to Janet Alleyn, who not only designed the book but, once again, took the art, photos, and manuscript and turned them into a beautiful book. Thanks goes to Judith Chaffin for her careful and conscientious editing. Special thanks to all the people at Cengage Learning who worked on this edition, including Lauren Oliveira, Morgan Carney, Hal Humphrey, and Dawn Giovannello.

Thanks to our friends who provided photos and to those reviewers who offered comments and suggestions for this edition, including:

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To the Student

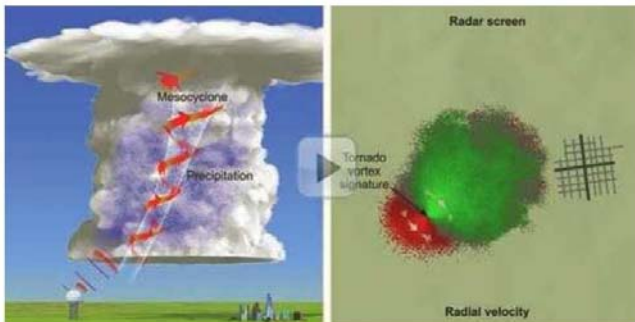
Learning about the atmosphere can be a fascinating and enjoyable experience. This book is intended to give you some insight into the workings of the atmosphere. However, for a real appreciation of your atmospheric environment, you must go outside and observe. Although mountains take millions of years to form, a cumulus cloud can develop into a raging thunderstorm in less than an hour. The atmosphere is always producing something new for us to behold. To help with your observations, a color Cloud Chart is at the back of the book for easy reference. Remove it and keep it with you. And, remember, all of the concepts and ideas in this book are manifested out there for you to discover and enjoy. Please take the time to look.

Donald Ahrens and Robert Henson

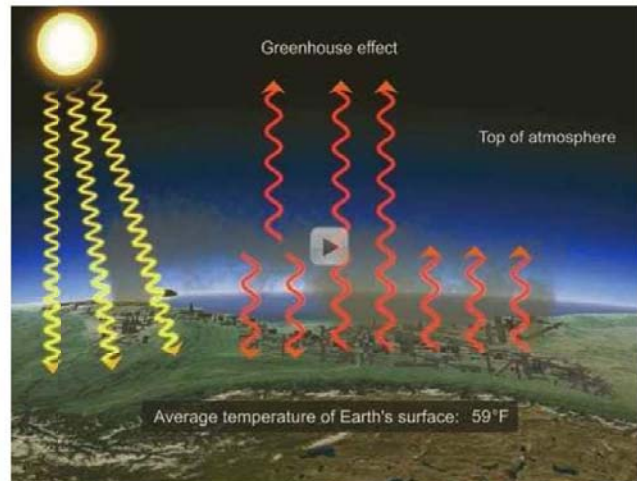
EXPLORE THE CONCEPT ANIMATIONS

These animations have been carefully created to bring to life key points in the chapters. They are also the perfect tool to help refresh students' memories of previous concepts, so they can keep building on knowledge already

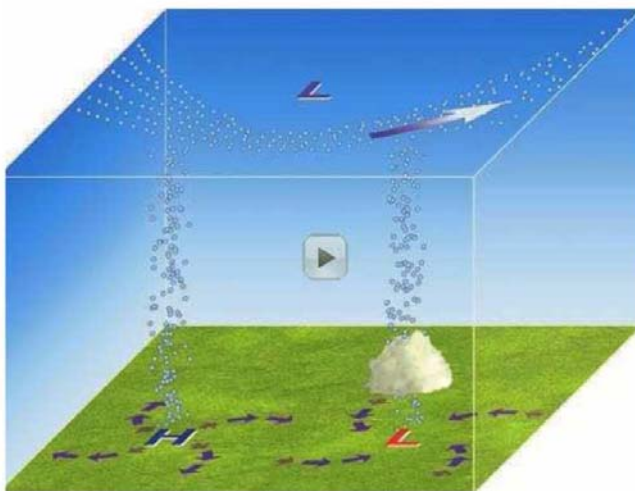
acquired. Concept Animations are accessed through the MindTap platform, which can be acquired separately or together with print or looseleaf versions of this book. Some examples of Concept Animations are shown here.



Doppler radar images are used extensively throughout this book. To better understand Doppler radar images, watch all 4 parts of this *Doppler Radar* animation (Chapters 1, 5, and 10).



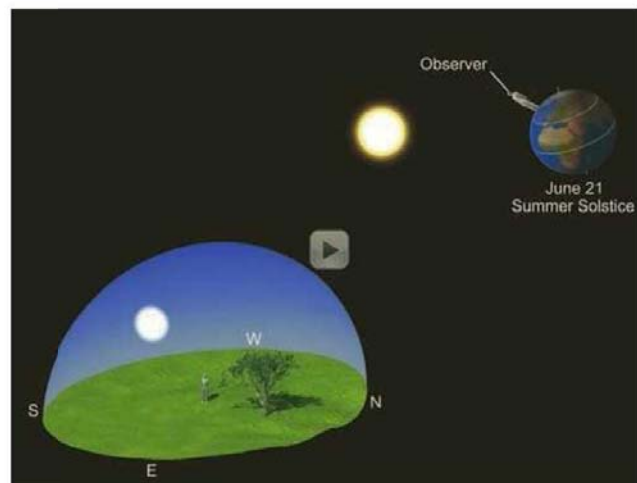
For a visual interpretation of the energy emitted by the earth without and with a greenhouse effect, watch the *Greenhouse* animation (Chapter 2).



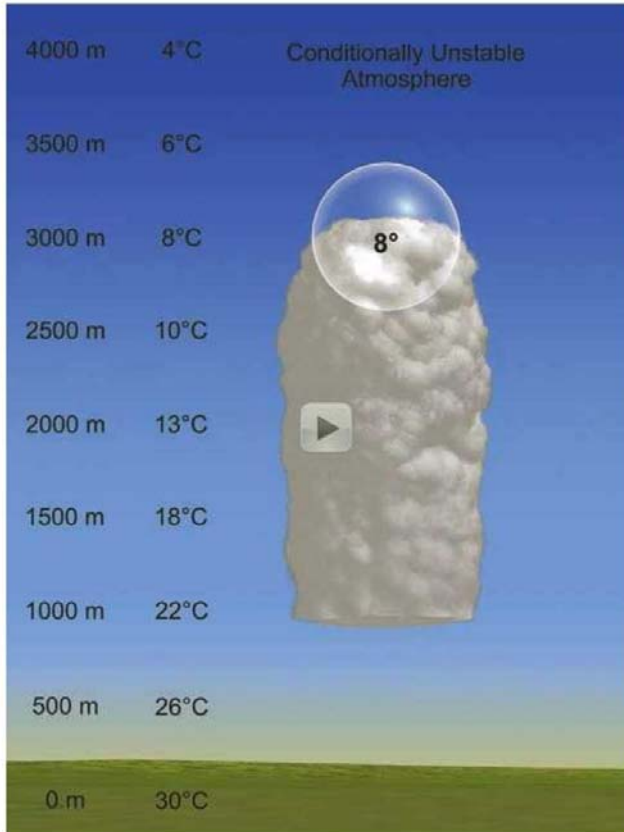
Learn about how air rises above an area of low atmospheric pressure and sinks above an area of high atmospheric pressure. *Converging and Diverging Air* (Chapters 1 and 8).

Additional Animations:

- Ice Crystals (Bergeron) Process (Chapter 5)
- General Circulation of the Atmosphere (Chapter 7)
- Geostrophic Wind (Chapter 6)
- Temperature versus Molecular Movement (Chapter 2)
- Condensation (Chapter 4)
- Air Temperature, Dew Point, and Relative Humidity (Chapter 4)
- Daily Temperature Changes Above the Surface (Chapter 3)



Seasons provides a complete picture of Earth revolving around the sun while it is tilted on its axis. While viewing this animation, look closely at how the sun is viewed by a mid-latitude observer at various times of the year (Chapter 2).



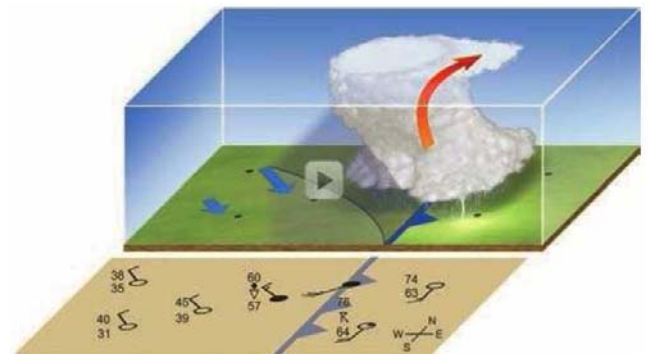
The concept of atmospheric stability can be a bit confusing, especially when comparing the temperature inside a rising air parcel to that of its surroundings. Watch *Stable Atmosphere* (Chapter 5) and the two animations *Unstable Atmosphere* and *Conditionally Unstable Atmosphere* (Chapters 5 and 10).



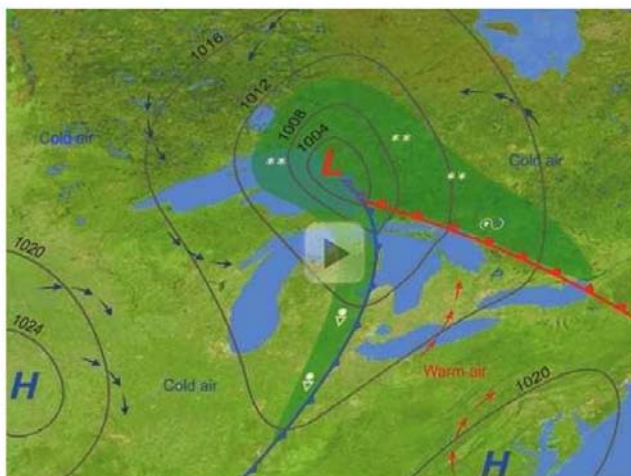
To view air rising over a mountain and the formation of a rain shadow desert, watch *Air Rising Up and Over a Mountain* (Chapters 5 and 7).



For a visual presentation of the Coriolis force, watch *Coriolis Force* (Chapter 6).



For a visualization of a cold front moving across the landscape, watch *Cold Front in Winter* (Chapters 8 and 9). To see a warm front actually move across the surface, watch *Warm Front in Winter* (Chapters 8 and 9).



For a visualization of the stages that a wave cyclone goes through from birth to decay, watch the animation entitled *Cyclogenesis* (Chapter 8).



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CHAPTER 1

Earth's Atmosphere

Contents

The Atmosphere and
the Scientific Method

Weather, Climate, and
Meteorology

Components of
Earth's Atmosphere

Vertical Structure of
the Atmosphere

I remember well a brilliant red balloon which kept me completely happy for a whole afternoon, until, while I was playing, a clumsy movement allowed it to escape. Spellbound, I gazed after it as it drifted silently away, gently swaying, growing smaller and smaller until it was only a red point in a blue sky. At that moment I realized, for the first time, the vastness above us: a huge space without visible limits. It was an apparent void, full of secrets, exerting an inexplicable power over all the Earth's inhabitants. I believe that many people, consciously or unconsciously, have been filled with awe by the immensity of the atmosphere. All our knowledge about the air, gathered over hundreds of years, has not diminished this feeling.

Theo Loeb sack, *Our Atmosphere*