THIRD EDITION

Essentials of Meteorology

An Invitation to the Atmosphere

C. DONALD AHRENS

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AN INVITATION TO THE ATMOSPHERE

C. Donald Ahrens
Modesto Junior College

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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 tornado.

In recent years, weather and climate have become front page news from such environmental issues as greenhouse warming and ozone depletion in the stratosphere to the global weather influences of El Niño. 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. The atmosphere will always provide challenges for us, but 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, the third edition maintains scientific integrity and includes up-to-date information on important topics, such as El Niño, ozone depletion, and global warming. Discussion of weather events, such as the destruction to Honduras wrought by Hurricane Mitch, also are included. As with previous editions, no special prerequisites are necessary.

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.

This edition, organized into fifteen chapters, 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 12, "Air Pollution," and Chapter 15, "Light, Color, and Atmospheric Optics," are both 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, and air temperature, humidity, clouds, precipitation, and winds. Then comes a chapter on air masses, fronts, and middle-latitude storms. Weather prediction and severe storms are next. A chapter on air pollution is followed by a chapter on global climate. A chapter on climate change is next. The final chapter deals with 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, applications, and special topics. Some include material that is not always found in introductory meteorology textbooks—subjects such as the history of meteorology, eddies and air pockets, and northeasters. Others help bridge theory and practice. Focus sections new to this edition include "When It Comes to Temperature, What's Normal?" and "Nuclear Winter, Cold Summers, and Dead Dinosaurs."

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. Many new "Did You Know?" items have been added to this edition.

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
- Summaries at the end of each chapter review the chapter's main ideas
- A list of key terms following each chapter allows students to review and reinforce their knowledge of the main concepts they have encountered
- Questions for Review act to check how well students assimilate the material
- Questions for Thought and Exploration are new to this edition and encourage students to synthesize learned concepts for a deeper understanding of the material. Some of the questions integrate the text with the Blue Skies CD-ROM

Eight appendices conclude the book. Some are more technical than the main text, such as Appendix B, "Equations and Constants." Others can be used in observing the weather, such as Appendix G, "The Beaufort Wind Scale." In addition, at the end of the book, a compilation of supplementary material, as well as an extensive glossary, is presented.

Third Edition Changes

To help visualize how exciting weather and climate can be, over 55 new color photographs and more than 50 new or revised color illustrations have been added to this edition. To complement the photographs and new art, the third edition of *Essentials of Meteorology* has been extensively updated and revised.

Chapter 1 still serves as a broad overview of the atmosphere, but the more advanced material on stratospheric ozone and the ozone hole has been placed in the chapter on air pollution (Chapter 12), next to the material on tropospheric ozone. Chapter 2, "Warming the Earth and the Atmosphere," contains additional information on the atmospheric greenhouse effect, while Chapter 3 contains a new focus section on temperature data. Chapter 5, "Cloud Development and Precipitation," now contains a section on Doppler radar and precipitation.

In Chapter 7 ("Atmospheric Circulations"), the section on El Niño and the Southern Oscillation has been expanded and updated to include the latest major El Niño event of 1997–1998. The chapter on air masses, fronts and middle-latitude cyclones (Chapter 8) has been restructured for clarity. The chapter on weather forecasting (Chapter 9) has been reorganized and updated to include the modernization of the National Weather Service.

Chapter 10 ("Thunderstorms and Tornadoes") has been revised with new art, photos, and Doppler radar images. Moreover, new to this chapter is information on supercell storms and bow echoes. New material on hurricane intensity has been added to Chapter 11.

Chapter 12, "Air Pollution," now contains the latest information on stratospheric ozone and a Focus section on the ozone hole over Antarctica. The chapter on global climate (which is now Chapter 13) contains several new photos to illustrate the vegetation found in various climatic regions. The chapter on climate change (Chapter 14) has been revised to include the latest material on global warming. Among the additions to this chapter are a Focus section on the demise of the dinosaurs and a Focus section on the ocean conveyor belt and climate change.

Acknowledgments

A special thank-you to the many individuals who have contributed to the production of this third edition. Thanks go to my friends and colleagues who provided me with their beautiful photographs. Thanks go to Lita Teixeira, Debbie Waters, and Vicki Groff for their careful reading of the book and for their invaluable assistance. I am most indebted to Janet Bollow who, once again, put a tremendous effort into ensuring a beautiful product. Thanks to Stuart Kenter for his careful editing and for his researching some of the photos.

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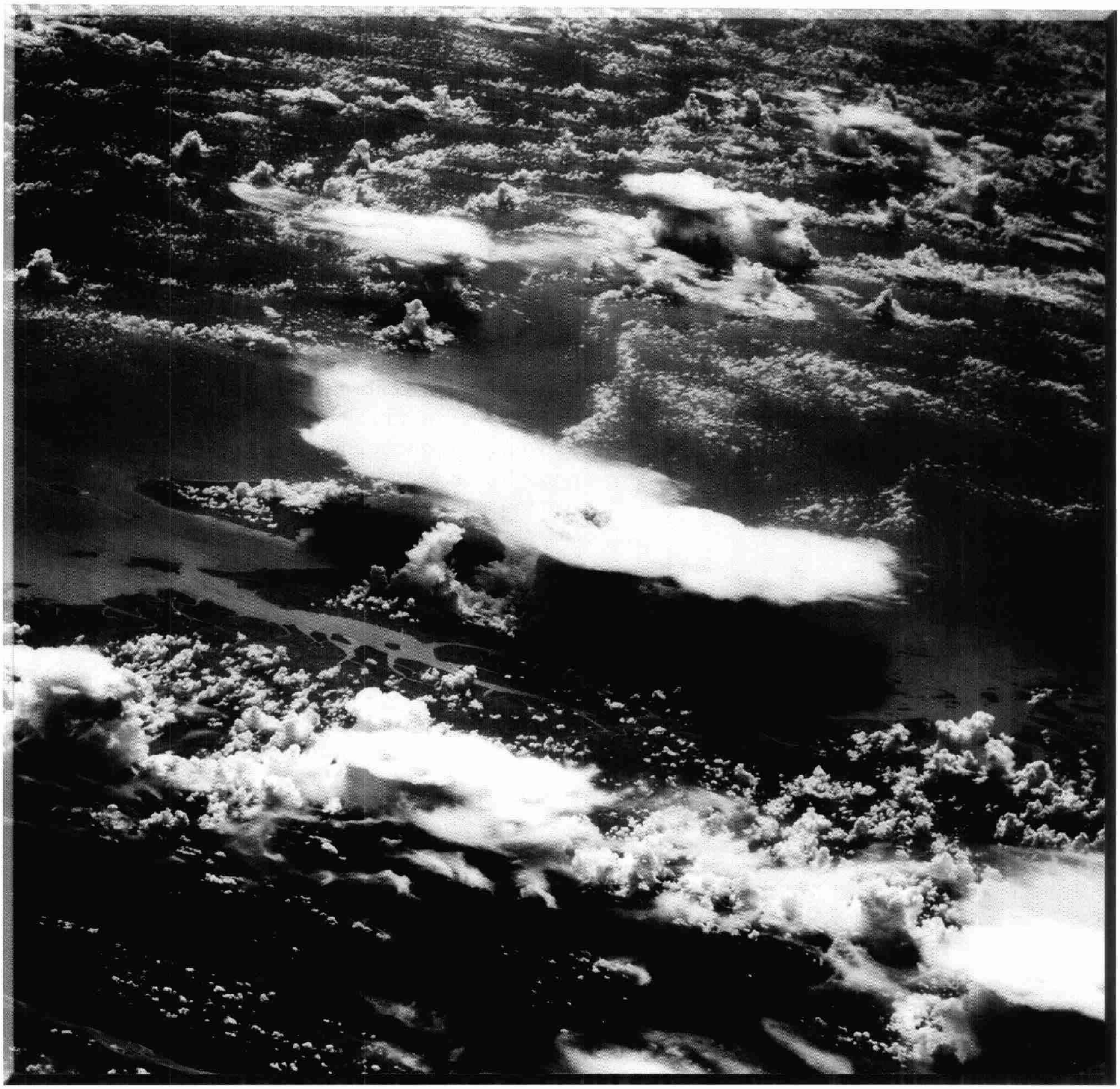
To the Student

Learning about the atmosphere can be an enjoyable experience, especially if you become involved. This book is intended to give you some insight into the workings of the atmosphere, but for a real appreciation of your atmospheric environment, you must go outside and observe. Mountains take millions of years to form, while a cumulus cloud can develop into a raging thunderstorm in less than an hour. To help with your observations, a color Cloud Chart is bound toward the back of the book for easy reference. Remove it and keep it with you. And remember, all of the information in this book is out there—please, take the time to look.

Donald Ahrens

Your text is accompanied by **Student Resources,** an online resource center dedicated to this text. For access to this helpful and practical resource, point your web browser to **http://www.brookscole.com/product/0534372007s**. Follow the online instructions to log in. You will be asked to supply the user name and text ISBN at the initial registration page. Your user name is **metfan** and your text ISBN is **0534372007.**



We live at the bottom of a swirling ocean of air. Here, air billowing up from the earth's surface forms into clouds and thunderstorms over the warm, tropical Pacific Ocean. (Photo: NASA.)

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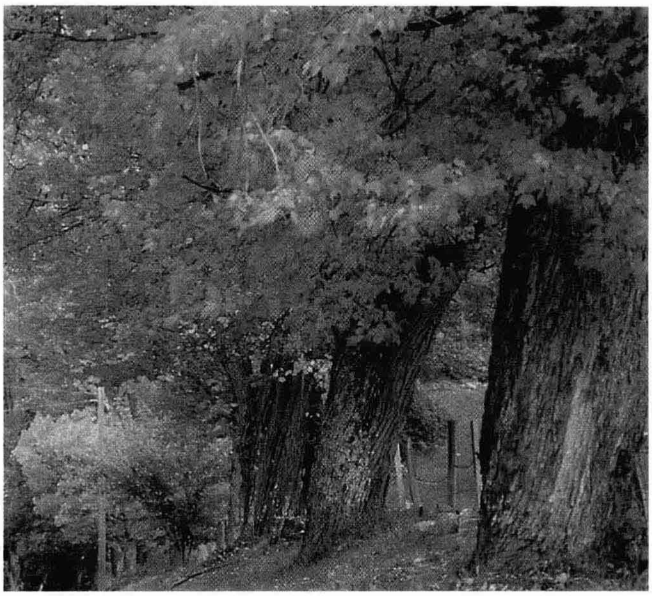

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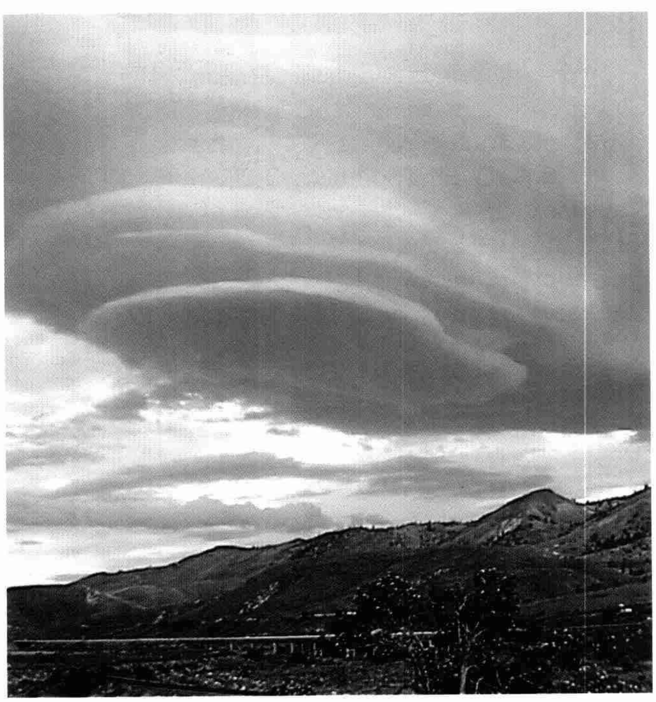

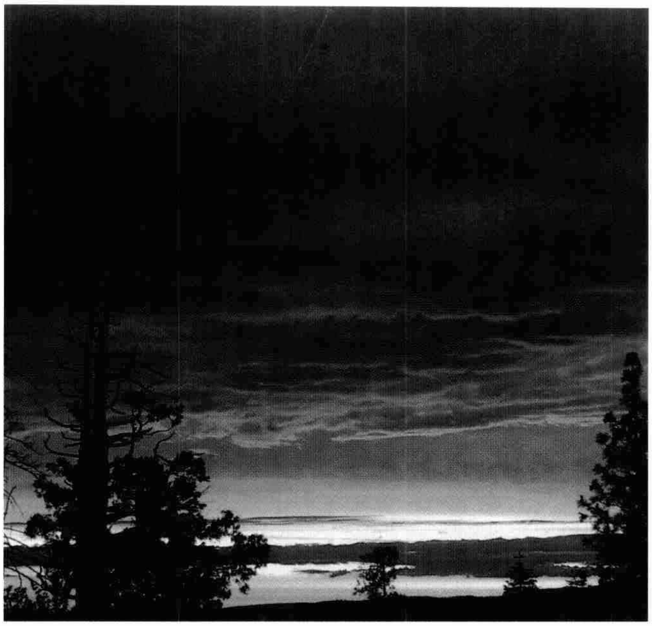

1

The Earth's Atmosphere

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

Theo Loebsack, *Our Atmosphere*

Our *atmosphere* is a delicate life-giving blanket of air that surrounds the fragile earth. In one way or another, it influences everything we see and hear—it is intimately connected to our lives. Air is with us from birth, and we cannot detach ourselves from its presence. In the open air, we can travel for many thousands of kilometers in any horizontal direction, but should we move a mere eight kilometers above the surface, we would suffocate. We may be able to survive without food for a few weeks, or without water for a few days, but, without our atmosphere, we would not survive more than a few minutes. Just as fish are confined to an environment of water, so we are confined to an ocean of air. Anywhere we go, it must go with us.

The earth without an atmosphere would have no lakes or oceans. There would be no sounds, no clouds, no red sunsets. The beautiful pageantry of the sky would be absent. It would be unimaginably cold at night and unbearably hot during the day. All things on the earth would be at the mercy of an intense sun beating down upon a planet utterly parched.

Living on the surface of the earth, we have adapted so completely to our environment of air that we sometimes forget how truly remarkable this substance is. Even though air is tasteless, odorless, and (most of the time) invisible, it protects us from the scorching rays of the sun and provides us with a mixture of gases that allows life to flourish. Because we cannot see, smell, or taste air, it may seem surprising that between your eyes and the pages of this book are trillions of air molecules. Some of these may have been in a cloud only yesterday, or over another continent last week, or perhaps part of the life-giving breath of a person who lived hundreds of years ago.

Warmth for our planet is provided primarily by the sun's energy. At an average distance from the sun of nearly 150 million kilometers (km), or 93 million miles (mi), the earth intercepts only a very small fraction of the sun's total energy output. However, it is this radiant energy* that drives the atmosphere into the patterns of everyday wind and weather, and allows life to flourish.

At its surface, the earth maintains an average temperature of about 15°C (59°F).† Although this temperature is mild, the earth experiences a wide range of temperatures, as readings can drop below –85°C (–121°F) during a frigid Antarctic night and climb during the day, to above 50°C (122°F) on the oppressively hot, subtropical desert.

In this chapter, we will examine a number of important concepts and ideas about the earth's atmosphere, many of which will be expanded in subsequent chapters.

*Radiant energy, or radiation, is energy transferred in the form of waves that have electrical and magnetic properties. The light that we see is radiation, as is ultraviolet light. More on this important topic is given in Chapter 2.

†The abbreviation °C is used when measuring temperature in degrees Celsius, and °F is the abbreviation for degrees Fahrenheit. More information about temperature scales is given in Appendix A and in Chapter 2.

Did You Know?

If the earth were to shrink to the size of a large beach ball, its inhabitable atmosphere would be thinner than a piece of paper.

Overview of the Earth's Atmosphere

The earth's **atmosphere** is a thin, gaseous envelope comprised mostly of nitrogen (N_2) and oxygen (O_2), with small amounts of other gases, such as water vapor (H_2O) and carbon dioxide (CO_2). Nested in the atmosphere are clouds of liquid water and ice crystals.

The thin blue area near the horizon in Fig. 1.1 represents the most dense part of the atmosphere. Although our atmosphere extends upward for many hundreds of kilometers, almost 99 percent of the atmosphere lies within a mere 30 km (about 19 mi) of the earth's surface. This thin blanket of air constantly shields the surface and its inhabitants from the sun's dangerous ultraviolet radiant energy, as well as from the onslaught of material from interplanetary space. There is no definite upper limit to the atmosphere; rather, it becomes thinner and thinner, eventually merging with empty space, which surrounds all the planets.

COMPOSITION OF THE ATMOSPHERE Table 1.1 shows the various gases present in a volume of air near the earth's surface. Notice that **nitrogen** (N_2) occupies about 78 percent and **oxygen** (O_2) about 21 percent of the total volume. If all the other gases are removed, these percentages for nitrogen and oxygen hold fairly constant up to an elevation of about 80 km (or 50 mi).

At the surface, there is a balance between destruction (output) and production (input) of these gases. For example, nitrogen is removed from the atmosphere primarily by biological processes that involve soil bacteria. It is returned to the atmosphere mainly through the decaying of plant and animal matter. Oxygen, on the other hand, is removed from the atmosphere when organic matter decays and when oxygen combines with other

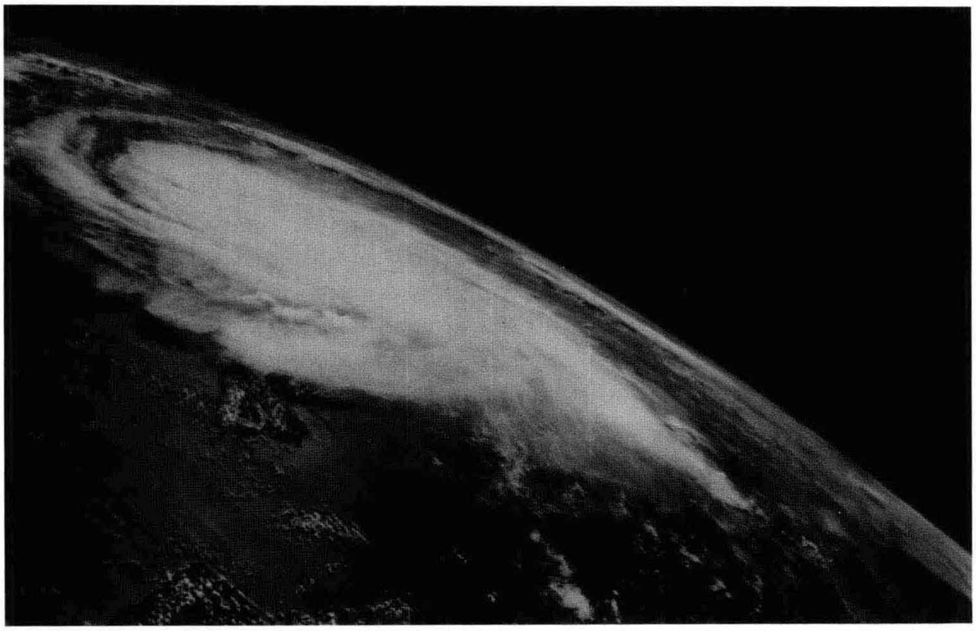

FIGURE 1.1
The earth's atmosphere as viewed from space. The thin blue area near the horizon shows the shallowness of the earth's atmosphere.

substances, producing oxides. It is also taken from the atmosphere during breathing, as the lungs take in oxygen and release carbon dioxide. The addition of oxygen to the atmosphere occurs during photosynthesis, as plants, in the presence of sunlight, combine carbon dioxide and water to produce sugar and oxygen.

The concentration of the invisible gas **water vapor,** however, varies greatly from place to place, and from time to time. Close to the surface in warm, steamy, tropical locations, water vapor may account for up to 4 percent of the atmospheric gases, whereas in colder arctic areas, its concentration may dwindle to a mere fraction of a percent. Water vapor molecules are, of course, invisible. They become visible only when they transform into larger liquid or solid particles, such as cloud droplets and ice crystals. The changing of water vapor into liquid water is called *condensation,* whereas the process of liquid water becoming water vapor is called *evaporation.* In the lower atmosphere, water is everywhere. It is the only substance that exists as a gas, a liquid, and a solid at those temperatures and pressures normally found near the earth's surface (see Fig. 1.2).

Water vapor is an *extremely* important gas in our atmosphere. Not only does it form into both liquid and

TABLE 1.1 Composition of the Atmosphere Near the Earth's Surface

Permanent Gases			Variable Gases – TRACE GASES			
Gas	*Symbol*	*Percent (by Volume) Dry Air*	*Gas (and Particles)*	*Symbol*	*Percent (by Volume)*	*Parts per Million (ppm)**
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.037	368*
Argon	Ar	0.93	Methane	CH_4	0.00017	1.7
Neon	Ne	0.0018	Nitrous oxide	N_2O	0.00003	0.3
Helium	He	0.0005	Ozone	O_3	0.000004	0.04†
Hydrogen	H_2	0.00006	Particles (dust, soot, etc.)		0.000001	0.01–0.15
Xenon	Xe	0.000009	Chlorofluorocarbons (CFCs)		0.00000002	0.0002

*For CO_2, 368 parts per million means that out of every million air molecules, 368 are CO_2 molecules.

†Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.

solid cloud particles that grow in size and fall to earth as precipitation, but it also releases large amounts of heat—called *latent heat*—when it changes from vapor into liquid water or ice. Latent heat is an important source of atmospheric energy, especially for storms, such as thunderstorms and hurricanes. Moreover, water vapor is a potent *greenhouse gas* because it strongly absorbs a portion of the earth's outgoing radiant energy (somewhat like the glass of a greenhouse prevents the heat inside from escaping and mixing with the outside air). Thus, water vapor plays a significant role in the earth's heat-energy balance.

Carbon dioxide (CO_2), a natural component of the atmosphere, occupies a small (but important) percent of a volume of air, about 0.037 percent. Carbon dioxide enters the atmosphere mainly from the decay of vegetation, but it also comes from volcanic eruptions, the exhalations of animal life, from the burning of fossil fuels (such as coal, oil, and natural gas), and from deforestation. The removal of CO_2 from the atmosphere takes place during *photosynthesis,* as plants consume CO_2 to produce green matter. The CO_2 is then stored in roots, branches, and leaves. The oceans act as a huge reservoir for CO_2, as phytoplankton (tiny drifting plants) in surface water fix CO_2 into organic tissues. Carbon dioxide that dissolves directly into surface water mixes downward and circulates through greater depths. Estimates are that the oceans hold more than 50 times the total atmospheric CO_2 content.

Figure 1.3 reveals that the atmospheric concentration of CO_2 has risen more than 15 percent since 1958, when it was first measured at Mauna Loa Observatory in Hawaii. This increase means that CO_2 is entering the atmosphere at a greater rate than it is being removed. The increase appears to be due mainly to the burning of fossil fuels; however, deforestation also plays a role as cut timber, burned or left to rot, releases CO_2 directly into the air, perhaps accounting for about 20 percent of the observed increase. Measurements of CO_2 also come from ice cores. In Greenland and Antarctica, for example, tiny bubbles of air trapped within the ice sheets reveal that before the industrial revolution, CO_2 levels were stable at about 280 parts per million (ppm). Since the early 1800s, however, CO_2 levels have increased by as much as 25 percent. With CO_2 levels presently increasing by about 0.4 percent annually (1.5 ppm/year), scientists now estimate that the concentration of CO_2 will likely rise from its current value of about 368 ppm to a value near 500 ppm toward the end of this century.

Carbon dioxide is another important greenhouse gas because, like water vapor, it traps a portion of the earth's outgoing energy. Consequently, with everything else being equal, as the atmospheric concentration of CO_2 increases, so should the average global surface air temperature. Most of the mathematical model experiments that predict future atmospheric conditions estimate that increasing levels of CO_2 (and other greenhouse gases) will result in a *global warming* of surface air between 1°C and 3.5°C (about 2°F to 6°F) by the year 2100. Such warming (as we will learn in more detail in Chapter 14) could result in a variety of consequences, such as increasing precipitation in certain areas and reducing it in others as the global air currents that guide the major

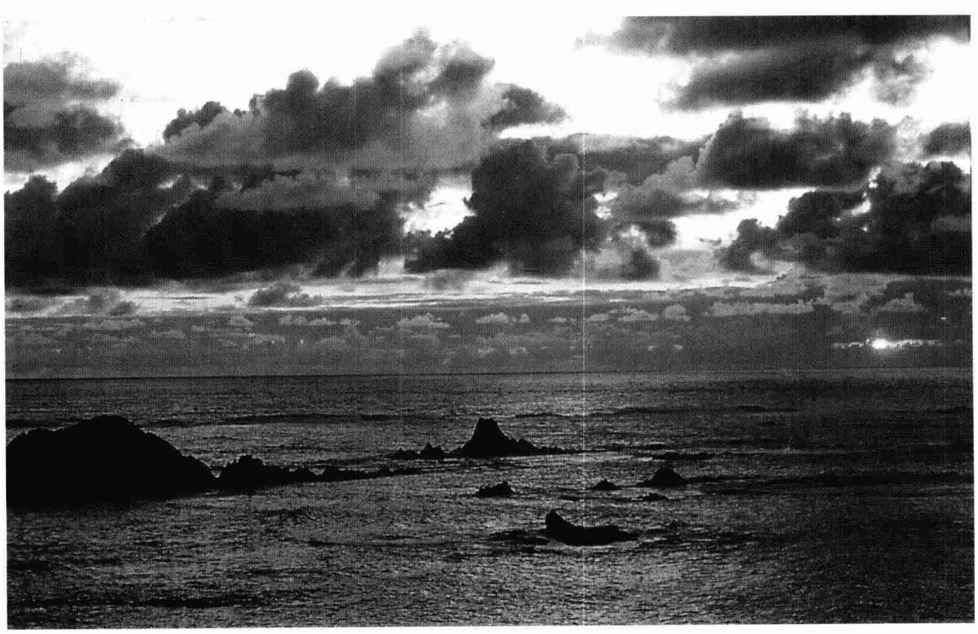

FIGURE 1.2
The earth's atmosphere is a rich mixture of many gases, with clouds of condensed water vapor and ice crystals. Here, water evaporates from the ocean's surface. Rising air currents then transform the invisible water vapor into many billions of tiny liquid droplets that appear as puffy cumulus clouds. If the rising air in the cloud should extend to greater heights, where air temperatures are quite low, some of the liquid droplets would freeze into minute ice crystals.