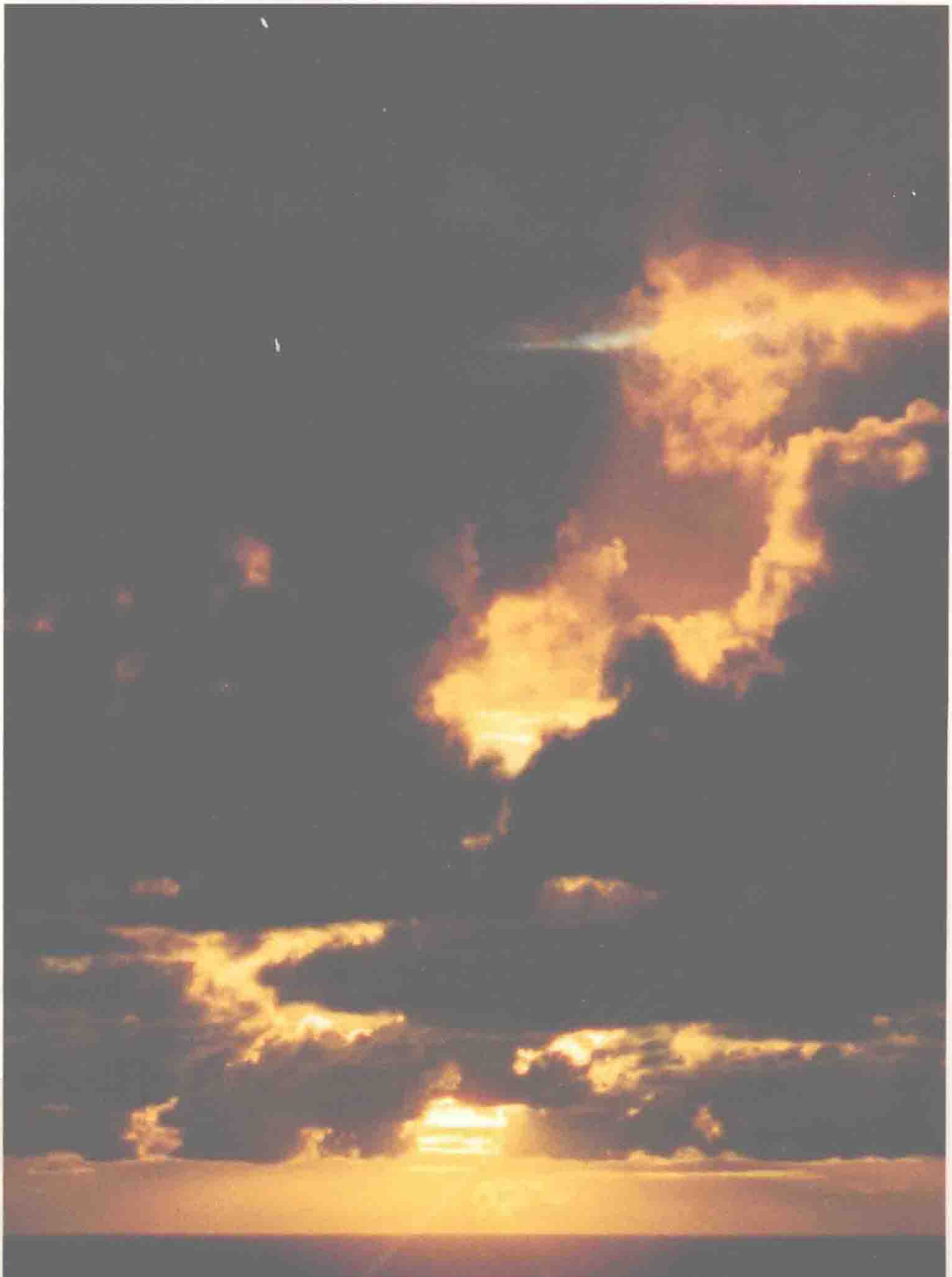
Meteorology

SIXTH EDITION



Richard A. Anthes

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Preface

Since 1985, when the 5th edition of *Meteorology* was published, there has been growing awareness that the increasing human population and its associated activities are significantly altering the atmosphere, and possibly the weather and climate. In 1985, a dramatic reduction in stratospheric ozone over Antarctica during the Spring months was confirmed. Subsequent expeditions there indicated that synthetic chlorine compounds were responsible for the destruction of the ozone layer, which protects life at the earth's surface from the sun's deadly ultraviolet rays.

There has also been mounting evidence that emissions of such gases as carbon dioxide and methane by human activities (for example, the burning of fossil fuels and in agricultural processes) have the potential to create a warmer climate than any ever experienced by civilization. Some scientists argue that such a change is only decades away.

Because of the importance of the accelerating changes in the environment caused by humans, the 6th edition of *Meteorology* includes a new chapter, "Global Change." This chapter discusses the basic changes that have already occurred in the atmosphere due to human activities, and also predicts dramatic changes that may occur in the future. In addition to the new chapter on global change, the 6th edition is updated throughout with new theories, data, and figures.

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Contents

1
The Air Around Us

1.1 INTRODUCTION

Relative to the diameter of the earth, the atmosphere is an extremely thin gaseous envelope; if the earth were the size of a peach, the atmosphere would be thinner than the fuzz on the peach. Yet all life on earth depends on this thin veil. Aside from the use of its constitutents in biological processes, the atmosphere controls life in many ways. It acts as an umbrella or shield, filtering various types of electromagnetic radiation and high-energy particles from the sun and space. Most meteorites are burned up before they can penetrate to the earth's surface. Winds transport heat and moisture and, in the process, mix the air and create more uniform conditions on the earth than would otherwise exist. The same winds drive the ocean currents, produce waves, erode the soil and transport pollen and insects. Weather destroys human structures and disrupts massive systems of communication and transportation. The sounds we hear, the scents we smell, and the sights we see are all affected by the state of the atmosphere.

Meteorology is a science that seeks a more complete understanding of the physical processes that determine weather and climate. From this improved understanding comes the important practical application of prediction of future weather, ranging from short-range warnings of severe weather to long-range outlooks of seasonal temperatures and precipitation. In addition, meteorology can provide much needed information about the interactions between human activities and the environment; for example, how climate and air quality are modified by industrial and agricultural practices.

Prediction is a fundamental task of all sciences. Yet, after more than a hundred years of public weather forecasting—and in spite of steady improvements—forecasts are still the subject of countless jokes. For a period of one to three days, the accuracy of weather forecasts is high—though certainly not perfect—but beyond a few days, the reliability falls off markedly. Yet meteorologists deal with the same set of laws used by other physical scientists. If the astronomer can forecast an eclipse years ahead without a miss, why can't the meteorologist foretell exactly when tomorrow's rain will begin?

We hope the answer to this question will become clear in this book. The complexity of weather patterns is so great that it will never be possible to completely describe the state of the atmosphere, let alone forecast its future condition in detail. The motions of the atmosphere are composed of convective "cells" and vortices (whirlpools) of many sizes, one superimposed on another. The "chaotic" appearance of lake or ocean waves on a windy day would be more than equalled in the atmosphere if air motions could be seen. Yet each whirl plays a role in the total weather picture. It is perhaps not surprising that progress in understanding the atmosphere so that its behavior can be predicted has been painfully slow.

Existence in harmony with the environment may be natural for most forms of life, but it is not for humans with their complex social and technological systems. Climatologists have long been concerned with using knowledge about the atmosphere's characteristics to maximize agricultural production. More recently, with the explosive growth of the human population, scientists have become aware that emission of trace gases by human activities and changing land-surface characteristics such as deforestation and urbanization can significantly affect the climate and weather. These changes are discussed in Chapter 8.

This book concerns primarily the weather phenomena that occur in the lowest 10 kilometers (6 miles) of the atmosphere. After this introductory chapter, which deals with the general properties of the atmosphere and measurements, two basic concepts are employed in the discussion of atmospheric processes. One is that the atmosphere is a giant *heat engine*. An engine transforms energy from one type to another. In the atmosphere, radiant energy from the sun is transformed to heat. Because the heat energy of the atmosphere varies from place to place, some of it is changed into kinetic energy; i.e., energy of motion. Man-made engines work the same way, of course. If the gases in the cylinder of a gasoline engine were not hotter than those on the outside, the pistons would not move. Examination of the ways in which different energy levels are created within the atmosphere is a convenient way to decipher the complex processes.

The other concept used in this book is that atmospheric processes and motions exist in a large range of sizes or **scales**. In the case of air motion, for example, there exists a hierarchy of flow systems that range from giant "eddies," which may cover 10 percent or more of the area of the globe, to tiny whirls, which scatter the dust on a road. Although there is an interplay between each size and its smaller and bigger "brothers," they differ in their characteristics of air motion and weather and in the relative significance of the various atmospheric forces. For example, the circulation pattern of a middle-latitude cyclone has a horizontal dimension about a hundred times that of its vertical extent, but in a thunderstorm the depth is about the same as the width. In the case of the cyclone, the earth's rotation is a significant factor in determining the flow. This is not so in the case of the thunderstorm convective cell.

1.2 PROPERTIES OF THE ATMOSPHERE

Origin and Composition

The atmosphere that exists today evolved slowly over millions of years after the formation of the earth, which occurred approximately 4.5 billion years ago. The original gases that formed the early atmosphere were emitted from volcanoes. However, these volcanic gases were considerably different from the gases that constitute our present atmosphere. Table 1.1 shows the composition of gases emitted from present-day Hawaiian volcanoes, while Table 1.2 lists the composition of today's lower atmosphere. Because there is evidence that the composition of the earliest volcanoes was similar to that of present volcanoes, the original atmosphere must have undergone considerable transformation to reach the benign, life-supporting mixture of gases that we have today.

Most of the **water vapor** in the early volcanic eruptions condensed, filling the ocean basins. The carbon dioxide reacted with minerals to form carbonates, while much of the hydrogen escaped the earth's gravitational field. Free oxygen probably formed after the first quarter of the earth's life and after the formation of the first life, which consisted of simple anaerobic plants. These one-celled organisms could produce oxygen through photosynthesis, in which carbon dioxide and water to combine to produce carbohydrates and oxygen according to the reaction.

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \textbf{(1.1)}$$

It has been estimated that 95 percent of the total oxygen was produced in this way.

TABLE 1.1
Percentage by volume of gases emitted by Hawaiian volcanoes.

Gas	Percentage
Water vapor (H_2O)	79.3
Carbon dioxide (CO_2)	11.6
Sulfur dioxide (SO_2)	6.5
Nitrogen (N_2)	1.3
Hydrogen (H_2)	0.6
Other	0.7
Total	100.0

TABLE 1.2
Composition of present atmosphere near surface.

Gas	Percentage
Nitrogen (N_2)	78.08
Oxygen (O_2)	20.95
Argon (A)	0.93
Carbon dioxide (CO_2)	0.03
Water vapor (H_2O)	0.00–4.0 (variable)

Below 80 kilometers, the gases of the atmosphere are relatively well mixed. In this layer, known as the **homosphere,** the proportion of each constituent gas, with few exceptions, is fairly constant throughout. In contrast, in the **heterosphere,** above 80 kilometers, the various gases have tended to stratify in accordance with their weights, as occurs with liquids of different densities.

The Lower Atmosphere

In addition to the major constituents listed in Table 1.2, a host of other gases such as neon, helium, methane, krypton, xenon, hydrogen, and ozone together comprise about a hundredth of 1 percent. The chemical properties of these gases are of considerable interest to the biologist because some, such as nitrogen, oxygen, and carbon dioxide, are involved in life processes. Many of these trace gases are also of great interest because of the way they affect the radiation budget of the earth, and hence the climate. **Carbon dioxide**, water vapor, and other gases present in even smaller concentrations, such as methane and oxides of nitrogen, are called **"greenhouse gases"** because their effects on radiation received from the sun and emitted by the earth cause the surface of the earth to be much warmer than it would be in the absence of these gases. As discussed in Chapter 8, rapid increases in many of the greenhouse gases are likely to cause significant changes in the climate in the decades ahead.

Air always contains some water in the gaseous state, and sometimes the water vapor occupies as much as 4 percent of the volume. The amount, however, varies greatly in time and space. Water is the only substance that can exist in all three states—gas, liquid, and solid—at the temperatures that exist normally on the earth. The cycle of transition between these states goes on continuously and plays an important role in maintaining life. In addition, these *atmospheric phase changes* of water play another role that is significant to the meteorologist. During the transition from a liquid or solid to a vapor state, water molecules take up some heat energy, which they obtain from their surroundings. When they revert to the liquid or solid state, they release the same amount of energy to their environment. Thus, heat consumed at one place during evaporation may be released at an entirely different place during condensation. This is an effective way of transporting heat over great distances.

Ozone is found in very minute quantities near the surface of the earth, usually comprising less than two parts in a hundred million. If all the ozone in the atmosphere could be brought down to sea-level pressure and temperature, it would form a layer only about 3 millimeters thick. Although the concentration of ozone is low at all levels of the atmosphere, there is a sharp peak near the altitude of 25 kilometers. Despite the small quantities, ozone is quite significant in the radiant energy transfer that goes on in the atmosphere. Because of ozone's strong absorption of ultraviolet light from the sun, very little of this lethal radiation arrives at the surface of the earth. The ozone (O_3) of the atmosphere is believed to form when an atom of oxygen (O), a molecule of oxygen (O_2), and a third "catalytic" particle, such as nitrogen, collide. The atomic oxygen is formed in the atmosphere by the splitting of molecular oxygen under the action of very short-wave solar radiation. The maximum of ozone near 25 kilometers is apparently due to a balance of two factors—the availability of very short-wave solar energy to produce atomic oxygen, which is gradually depleted as it traverses the upper layers of the atmosphere, and a sufficient density of particles to bring about the collisions required.

As discussed in Chapter 8, in recent years major losses of **ozone** have occurred over Antarctica in the Southern Hemisphere springtime. These losses have been caused by chemical reactions involving human-made chlorofluorocarbons—CFCs—through complex reactions involving minute quantities of ice in the polar stratosphere.

Fairly high concentrations of ozone commonly occur in the lowest few hundred meters of the atmosphere, especially over urban areas. Ozone, a corrosive toxic gas, is an important constituent of the so-called "photochemical smog" that afflicts some large cities. The atomic oxygen required for the reaction described above is formed in smog principally through the action of solar radiation on nitrogen dioxide, a product of combustion.

A variety of solid particles are suspended in the air. These include fine dust particles swept up by the wind from exposed soils; soot from forest fires, industrial fires, industrial plants, and volcanoes; pollen and microorganisms lifted by the wind; meteoritic dust; and salts injected into the atmosphere when ocean spray is evaporated. Large particles are too heavy to remain long in the air, but there are many, so small that they cannot be seen individually with the naked eye, that remain suspended for months or even years. The minute particles of dust thrown high into the atmosphere by the violent eruption of the volcano Krakatoa in the East Indies in 1883 circled the globe for at least two years, producing magnificent sunrises and sunsets. More recently, the eruption of Chichón in Mexico on 28 March 1982 injected massive amounts of dust and sulfur dioxide into the atmosphere (Figure 7.8). As this dust circled the earth, solar radiation was reduced by as much as 20 percent at the surface in some locations, perhaps causing a decrease of surface temperature of about 1°C in the months following the eruption.

Many of these small dust particles act as centers, or **nuclei,** around which minute water drops or ice crystals form. (This will be discussed a little later on in

Chapter 2, under "Clouds" and "Precipitation".) Figure 1.1 shows the sizes of these nuclei and, for purposes of comparison, the sizes of air molecules and liquid and solid water particles.

Dust particles in the air, as well as water droplets and ice crystals, affect the transparency of the air. They not only reduce visibility, but also they prevent some of the sun's energy from penetrating to the surface of the earth. There has been some speculation that humans, who have been increasing the atmosphere's load of dust with factories and high-flying aircraft, may be changing the climate. Although humans are undoubtedly the biggest contributors of the grime in urban areas (where the number of dust particles can reach as high as several million per

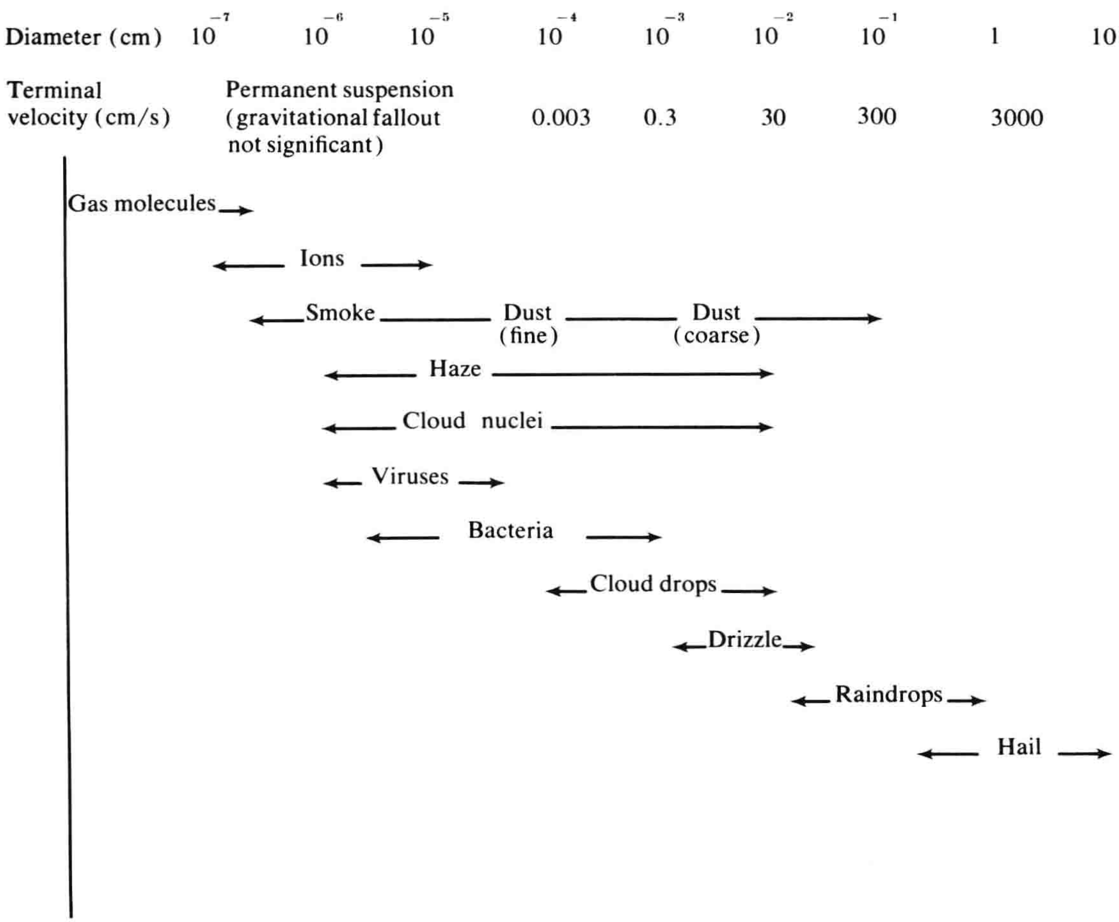

FIGURE 1.1
Diameter and terminal velocities (maximum fall velocities) of particles in the atmosphere.

cubic centimeter in smoke-laden air), our contribution to the overall dustiness of the atmosphere is small (at present) compared to such natural sources as volcanoes.

The Upper Atmosphere

The major constituents of the atmosphere remain virtually unchanged up to 80 or 90 kilometers, although there are significant variations in such minor constituents as ozone, dust, and water vapor. But above this level (at which point only 0.0002 percent of the total atmosphere remains), the relative amounts and types of gases change. The gases of the "thin" air of the heterosphere undergo various "photochemical" effects induced by the very short waves of ultraviolet and X-ray radiation from the sun. As a result of these photochemical reactions, molecular oxygen is split into two atoms and many molecules and atoms are ionized. That is, electrons have been ejected from their atoms, leaving them with an overall positive charge.

The entire layer from about 80 kilometers upward contains a large number of positively charged ions and free electrons and is therefore referred to as the **ionosphere.** This electrically charged portion of the atmosphere is very useful for radio communications, since it reflects radio waves. Around-the-world transmissions are accomplished by bouncing radio waves, which move in straight lines, between the ionosphere and the earth's surface.

The distribution of electron density with height fluctuates a great deal. There is a fairly regular daytime-to-nighttime change in the strength of some layers due to the changes in intensity of the solar radiation. In addition, there are occasional sudden ionospheric disturbances (S.I.D.s) and "ionospheric storms" that are associated with disturbances on the sun. An S.I.D. lasts from 15 to 30 minutes, and it is produced by bursts of ultraviolet energy from the sun, causing a sudden increase in the production of electrons. Because electrons absorb part of the radio energy that strikes them, a sudden increase in their number may actually smother the radio energy, leading to fadeouts of communications on the sunlit side of the earth. Ionospheric storms, which can occur during the day or night and last for hours or even days, are believed to be caused by a stream of charged particles emitted from the sun. These fast-moving particles, guided toward the poles by the earth's magnetic field, not only ionize the air, but also they produce the beautiful displays of aurora borealis (northern lights) and aurora australis (southern lights).

Temperature Distribution in the Vertical

The mean temperature distribution in the vertical shown in Figure 1.2 provides a basis for dividing the atmosphere into shells or layers. In the lowest of these layers, the **troposphere,** the temperature decreases with height, on the average, at the rate of 6.5°C/km (3.5°F/1000 ft). In this layer, vertical convection currents, induced primarily by the uneven heating of the layer by the earth's surface, keep the air fairly well stirred. Practically all clouds and weather and most of the dust and water vapor of the atmosphere are found in this turbulent layer. Its upper boundary,

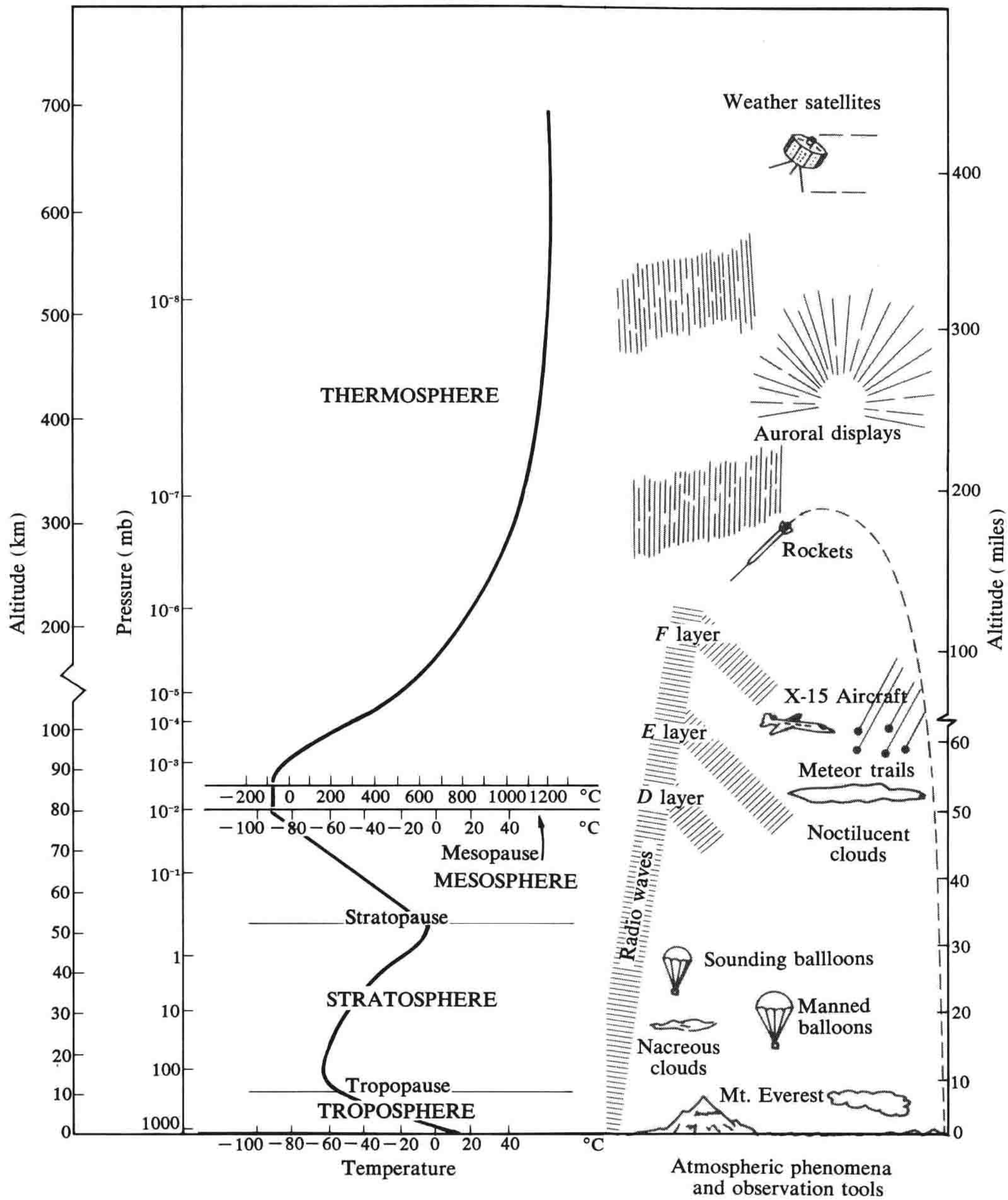

FIGURE 1.2
Vertical distribution of atmospheric temperature and phenomena.