

ATMOSPHERIC STRUCTURE. The vertical distribution of temperature, pressure, density, and composition of the atmosphere constitutes atmospheric structure. These quantities also vary with season and location in latitude and longitude, as well as from night to day; however under the topic of atmospheric structure, the focus is on the average variations with height above sea level.

Although it is impossible to define an absolute depth of the atmosphere, most of the atmosphere is confined to a narrow shell around the planet, with the pressure and density of air decreasing rapidly with altitude and gradually merging into the emptiness of space. Fifty percent of the mass of the atmosphere is within 5.5 kilometers (3.4 miles) of sea level; 90 percent is within about 16 kilometers (10 miles) of sea level, and 99.9 percent is below 49 kilometers (about 30 miles). Since the mean radius of the Earth is 6,370 kilometers (3,960 miles), the atmosphere is a very thin coating around our planet. At altitudes of 500 to 600 kilometers (about 350 miles) it is still possible to detect air, although the density of gases there is less than 10^{-12} (one trillionth) of that at sea level.

Figure 1 displays the vertical temperature structure and the pressure distribution of the atmosphere. The names given to the various layers, defined based on the temperature change with height, and the boundaries between these layers are also shown. The heights, pressures, and temperatures in the diagram are based on the U.S. Standard Atmosphere, which represents average conditions above the middle latitudes.

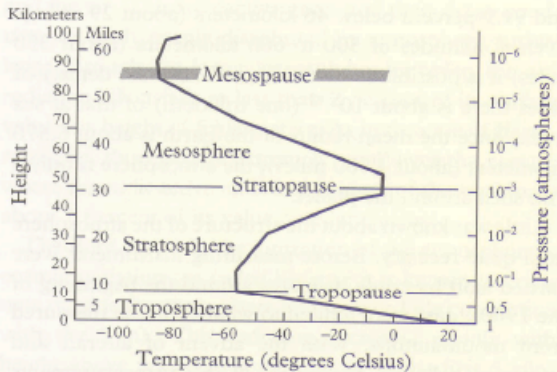
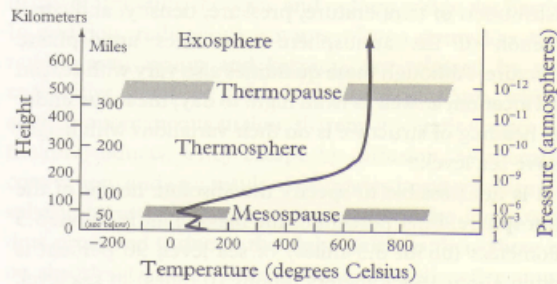
One might expect temperature to decrease steadily with height as the pressure decreases, since air cools as it expands into lower pressure regions, but this is not everywhere the case. Temperature cools with height throughout the troposphere, but it

then warms through the stratosphere, only to cool again through the mesosphere; finally it heats up in the thermosphere and exosphere. This distribution comes about through changing interactions among shortwave radiation from the Sun, longwave radiation from the Earth, and various gases in the air.

Scientists made rapid progress in understanding the structure of the atmosphere starting at the beginning of the 20th century. In 1902, Léon Teisserenc de Bort discovered the constant temperatures with height in the lower stratosphere with the use of rapidly-ascending hydrogen balloons. The inference of high temperatures around 50 kilometers was first made in 1923 by Frederick A. Lindemann and Gordon M. B. Dobson using measurements of meteor trails; study of long-distance sound propagation from cannonades during World War I and controlled experiments afterward provided further confirmation of the high temperatures near the stratopause. Meteorological rockets later allowed examination of the temperature and composition of upper layers of the atmosphere otherwise unreachable by weather balloons. Remote sensing of the atmosphere with satellites began in the early 1960s and remains extremely important for measuring properties of the different layers of the atmosphere.

Comment: There is are some typos in this figure: "Mesopause" should read "Mesopause" in both the upper panel and the lower panel.

Also, "29.2 inches" should read "29.92 inches"



ATMOSPHERIC STRUCTURE. Figure 1. *Structure of the atmosphere.* The distribution from the surface to 600 kilometers is shown in (a)—the exosphere continues on for an indeterminate distance. The lowest 100 kilometers are shown in more detail in (b). Vertical temperature distribution is from the U.S. Standard Atmosphere. The units of pressure are called atmospheres: 1 atmosphere equals 760 millimeters (29.2 inches) of mercury, or 1,013.25 millibars.

Composition of the Atmosphere. Air is a mixture of a number of gases, but the most abundant are molecular nitrogen (N_2) and molecular oxygen (O_2), with a tiny amount of the inert gas argon (Ar). These gases make up more than 99.9 percent of the mass of dry air; the ratio of the number of molecules of each is nearly constant up to a height of about 80 or 90 kilometers (about 60 miles). Other gases, whose relative concentrations vary, exist only in small quantities. The most important of these are water vapor (H_2O) and carbon dioxide (CO_2), which absorb and emit longwave radiation, and ozone (O_3), which

absorbs ultraviolet radiation from the Sun as well as some longwave radiation from the Earth. The distribution of these “trace” gases therefore affects the vertical temperature distribution. [See Longwave Radiation; Trace Gases.]

In addition to the layers of the atmosphere shown in Figure 1, which are defined based on temperature, there are also atmospheric layers defined based on the composition of air. The region below 80 to 90 kilometers is called the homosphere because the main constituents of air are homogeneously distributed regardless of weight. Above this level, molecules and atoms tend to separate, with the heavier gases beneath the lighter ones, in a layer called the heterosphere. Above about 64 kilometers (40 miles), in the upper homosphere and through the heterosphere, gases can be readily ionized by very shortwave radiation; that is, they can lose an electron from their atoms. Thus free electrons and ions are plentiful, giving this region the name ionosphere. The ionosphere is very important in long-range radio transmission. [See Ionosphere; Isotopes; Radiation; Shortwave Radiation.]

Ultraviolet radiation from the Sun interacts with oxygen molecules in the stratosphere to form ozone (O_3). The peak ozone concentration is found at about 25 kilometers (15.5 miles). Although the total amount is very small—only about 10 molecules of O_3 per million molecules of air at highest concentrations—ozone blocks much ultraviolet radiation that would otherwise damage living things. [See Ozone.]

The amount of water vapor in the air is quite variable and drops off rapidly with height. At peak concentrations near the surface, water vapor can make up around 4 percent of the mass of air, but in total water vapor makes up only around 0.33 percent of the mass of the atmosphere. At altitudes of about 10 kilometers the concentration of

water vapor is only about 1 percent of that at the ground, and higher levels have much less. This occurs primarily because very little water vapor is needed to saturate cold air, and excess water will precipitate as rain or snow.

Unlike water vapor and ozone, carbon dioxide is fairly well mixed in the air. Despite the low concentration of CO₂ (of 1 million molecules of air near the surface, only about 400 are CO₂) it is vital for photosynthesis as well as to maintaining the radiation balance. Water vapor and carbon dioxide both absorb little of the Sun's radiation, but they do absorb some of the Earth's radiation and reradiate it both upward and downward. This gives rise to the greenhouse effect, which keeps surface temperatures much warmer than they would otherwise be. [See Greenhouse Gases.]

Troposphere. The lowest atmospheric layer, the troposphere, is the thinnest of the layers, but it contains about 80 percent of the mass of the atmosphere. This is the region where most of what we know as “weather” takes place. Almost all clouds and precipitation form in the troposphere; weather fronts, hurricanes, and thunderstorms are tropospheric phenomena. Weather activity produces much upward and downward motion, so the troposphere is a region of mixing: the prefix “tropo” comes from the Greek word for “turning over.”

The lowest part of the troposphere—usually the lowest kilometer or so—is called the planetary boundary layer, where winds and temperatures are affected by characteristics of the underlying surface such as the height of vegetation and the temperature of the ground or water surface. Close to the surface, changes from daytime, when the Earth gains heat from the Sun, to nighttime, when it loses heat, are much greater than at higher altitudes in the troposphere.

The rate at which temperature decreases with height is called the lapse rate.

Above the boundary layer the troposphere's lapse rate averages about 6° to 7°C per kilometer, but the actual lapse rate in a given situation can be quite different. Sometimes the temperature is constant with height, or it may even increase with height in a shallow layer called an inversion. [See Inversion.]

When a dry air parcel rises without mixing heat with the environment, the lapse rate is approximately 10°C per kilometer. The average tropospheric lapse rate is less than this value primarily due to latent heating from the condensation of water vapor (although other processes such as large scale dynamical motions and radiation are important in parts of the troposphere as well). As warm, humid parcels rise, the air becomes cold enough for condensation to occur. The condensation results in a heating of the air parcels, with temperature increases of up to 50°C from condensation if all the water vapor of a humid parcel condenses out. Thus the air cools less rapidly as it rises and the lapse rate is less. [See Adiabatic Processes.] Condensation of water vapor is also a fundamental process in driving large scale circulations on Earth and in the dynamics of hurricanes [See Hurricanes].

The top of the troposphere, the tropopause, averages about 11 to 12 kilometers above sea level, but it can be as low as 7 to 8 kilometers in polar regions and as high as 16 to 18 kilometers in the tropics. The coldest tropopause temperatures are over the tropics, where it can be -70°C or colder, whereas over the poles tropopause temperatures of -40°C are found. The tropopause is generally higher in summer than in winter, and is expected to rise in warmer climates as well.

The tropopause is not always one continuous surface. Often there is a distinct tropopause above the tropics with a break at around 30° latitude where a new tropopause forms at a lower level. That tropopause slopes downward toward the pole and sometimes shows another break. A jet stream is often found in these tropopause breaks, which become regions of mixing between troposphere and stratosphere.

Stratosphere. Above the tropopause the stratosphere begins. The temperature usually stops decreasing; it becomes roughly constant at first and then begins to increase with height. The air in the stratosphere is very dry, generally having less than 0.05 percent of the maximum amount of water vapor found near the ground. Clouds are very rare here, except for occasional thunderstorm penetration in the lower part. The stratosphere ends at about 50 kilometers (31 miles) above the surface at the stratopause. Here the density of the air is only about one thousandth of that at sea level, but the temperature may be about 0°C and is sometimes near 20°C. Temperature increases in the stratosphere because of the presence of ozone. Ozone's absorption of ultraviolet radiation leads to warmer air that can sometimes reach temperatures as high as those found at the ground. This temperature distribution—warmer air above colder air—dampens vertical motion and mixing. This produces a stratified distribution of material, hence the name of this layer. There is little mixing across the tropopause; thus material injected into the stratosphere from an explosive volcano, for instance, can remain there for several years. [See Stratosphere.]

Above the Stratosphere. About 99.9 percent of the mass of the atmosphere is in the troposphere and stratosphere combined. Of the remaining mass, about 99 percent is in the next layer, called the mesosphere. The mesosphere, or middle atmosphere, begins above the stratopause. The amount of ozone here is very small, so the temperature ceases to

increase and begins to drop as the air loses heat to space by radiation, mainly from carbon dioxide. The temperature drops to near -90°C at the top of this layer, the mesopause, at an altitude of about 85 to 90 kilometers. The mesosphere is where meteors heat up and become visible. [See Mesosphere.]

Above the mesopause, in the thermosphere, the temperature begins to increase again because the gases there absorb the very short ultraviolet waves of the Sun's radiation; that radiation does not penetrate any lower. The thermosphere, together with the upper reaches of the mesosphere, is the region of the ionosphere. Auroras form in the thermosphere above both polar regions when gases in this layer are excited by particles from the Sun. The top of this layer, the thermopause, is not well defined. It is estimated to be at between 500 and 1,000 kilometers and changes radically with the amount of sunlight falling on it. The temperature in this region is not well defined either, but values over $1,000^{\circ}\text{C}$ are sometimes reported. [See Thermosphere.]

Beyond the thermosphere is a region called the exosphere. In this layer, the last of the atmospheric "spheres," the air is so rarefied that gas molecules may not collide with each other, and a few escape Earth's gravitational field altogether. In the exosphere the atmosphere gradually gives way to the radiation belts and magnetic fields of outer space.

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