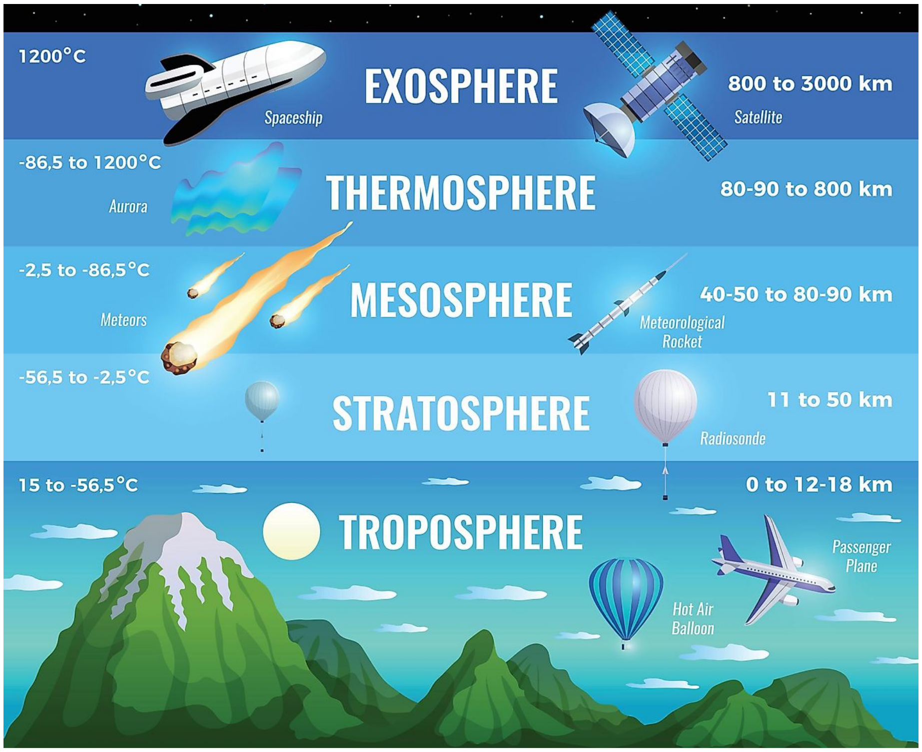
August 2022 Kenneth N Larson KJ6RZ

Chapter 10

Earth’s Atmosphere



(worldatlas.com)

www.skywave-radio.org

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10 Earth's Atmosphere

Earth's atmosphere is characterized by its change in density, pressure, temperature, and composition with altitude.

10.1 Atmospheric Air Density and Pressure

The downward force of gravity acting on air molecules causes air at any given level to compress air below it, increasing the density of air the closer one gets to ground level. Air density is considered greatest at sea level. However, air density is even greater at places like Death Valley, California which are below sea level. Figure 1 illustrates the change in air density with elevation. In Figure 1 a column of air stretches from ground level to the top of the atmosphere. The density of air, that is, the number of air molecules per cubic centimeter (light blue dots in Figure 1) is greatest at the bottom of the air column and decreases upward. Density initially decreases rapidly and then more slowly as altitude increases. The decrease of air density with altitude is illustrated in Figure 2. The right side of Figure 2 again shows a column of air. The number of air molecules (white dots) at the base of the air column vastly out numbers the density of white dots at an altitude of 200 km.

Atmospheric air pressure at any given altitude is simply the force exerted by a column of air molecules stretching from that point to the top of the atmosphere. In Figure 1 there are far fewer air molecules from the altitude shown on the right to the top of the atmosphere than from ground level to the top. Consequently, the air pressure part way up the column must be less than at ground level since there are far fewer molecules above that point. This means that atmospheric air pressure decreases with altitude.

The variation in air pressure with altitude is shown in Figure 3. Air pressure at sea level is defined as the force exerted by a column of air one square inch in cross sectional area that extends upward to the top of the atmosphere (to an altitude of approximately 500 km). Normal air pressure at sea level is 14.7 pounds per square inch which is equal to 1013 millibars (mb) as shown in Figure 3. This pressure may increase as a high pressure weather system passes or decrease in the presence of a low pressure system. The pressure gradients between low and high pressure systems is what causes winds to blow and the weather change. As illustrated in Figure 4 air flows from high pressure areas with warm sunny skies to low pressure systems often characterized by cool rainy days.

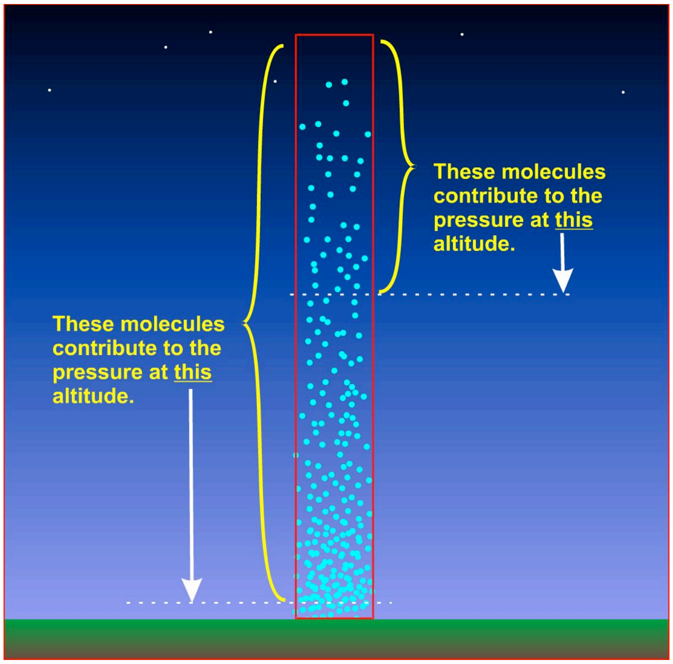

Figure 1 Air pressure (source: Penn State University Meteorology Dept.)

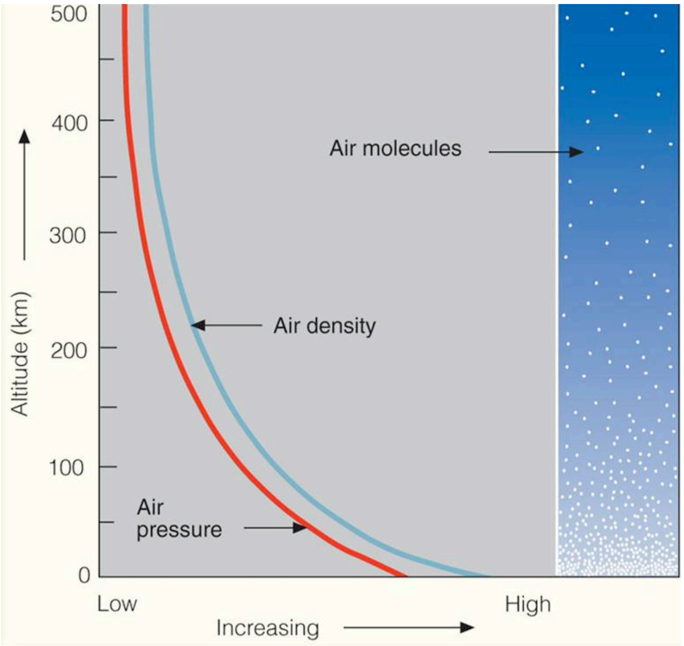

Figure 2 Air density and pressure vs altitude (source: Thomson Higher Education)

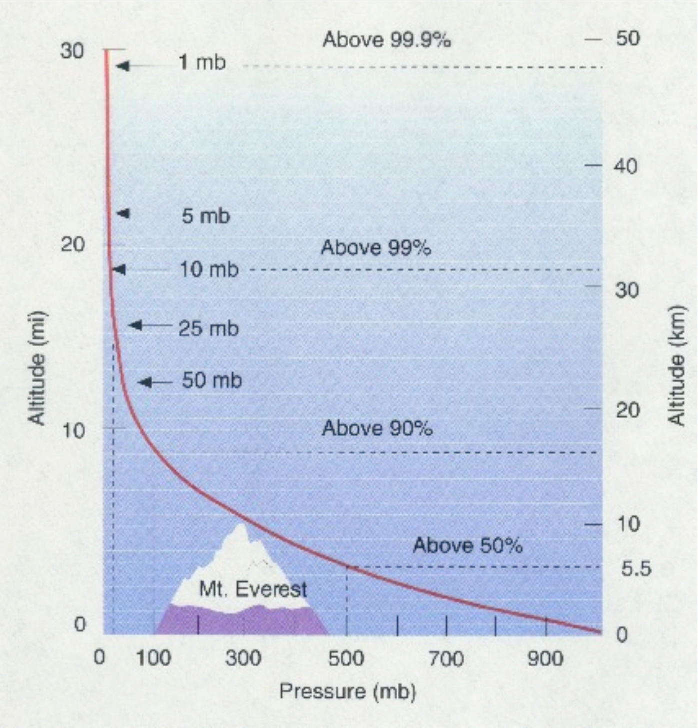

Figure 3 Atmospheric air pressure vs altitude (source: sites.millersville.edu)

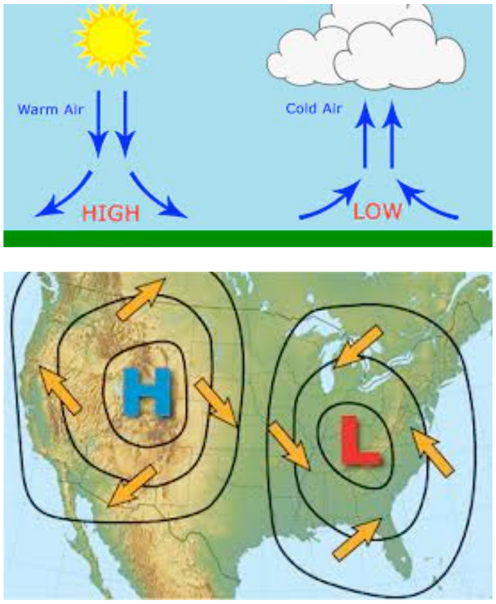

Figure 4 High and low pressure weather systems (source: weather.gov)

Several different units are used to measure atmospheric air pressure. The most common units of measure are shown in Table 1.

Air Pressure @ Sea Level	Units	Definition	Type
14.696	psi	pounds per square inch	Force
101,325	pascal (Pa)	newtons per square meter	Force
1013.25	millibars (mb)	hectopascal	Force
760	mm Hg	millimeters of Mercury	Barometric (barometer)
29.9212	in Hg	inches of Mercury	Barometric (barometer)

Table 1 Atmospheric pressure units of measure

Air pressure initially decreases rapidly and then more slowly as altitude increases (Figure 3). At an altitude of only 5.5 km air pressure has dropped from 1000 mb to 500 mb or to one half the pressure at sea level. This means that if you were at an altitude of 5.5 km (~ 18,000 ft) you would be above 50% of Earth's atmosphere. A commercial airliner flying at a typical altitude of 33,000 feet (10 km) is flying above roughly 70% of Earth's atmosphere. The ionosphere begins at around 50 km, above 99.9% of the atmosphere.

The atmosphere's air density, pressure and temperature are related by the gas law

$$PV = n\,RT$$

where

P = pressure
V = volume
n = number of moles
R = universal gas constant = 8.314 joules / (mole)(K^{o})
T= temperature in degrees kelvin (K^{o}).

In the above equation one mole is the quantity of a substance whose mass in grams is numerically equal to the substance's molecular weight.

Density ρ is the number of moles per unit volume. That is

$$\rho = \frac{n}{V}$$

In terms of density, the gas law can be written as

$$P = \rho R T$$

Since R is a constant, pressure is proportional to density and temperature, that is

$$P \propto \rho T$$

Pressure can also be defined as

$$P = P_0 e^{-h/H}$$

In this equation

h = height or altitude
P = pressure
P_0 = pressure at h = 0
H = scale height

Scale height is in turn

$$H = \frac{kT}{mg}$$

where

m = mass of a single gas molecule
g = acceleration of gravity

The significance of scale height is that it is the distance over which the air density ρ falls by a factor of e = 2.718 provided that T, m, and g are constant.

10.2 Atmospheric Air Temperature

The variation of atmospheric air temperature with altitude (Figure 5) is far more complex than the vertical structure of air density and pressure.

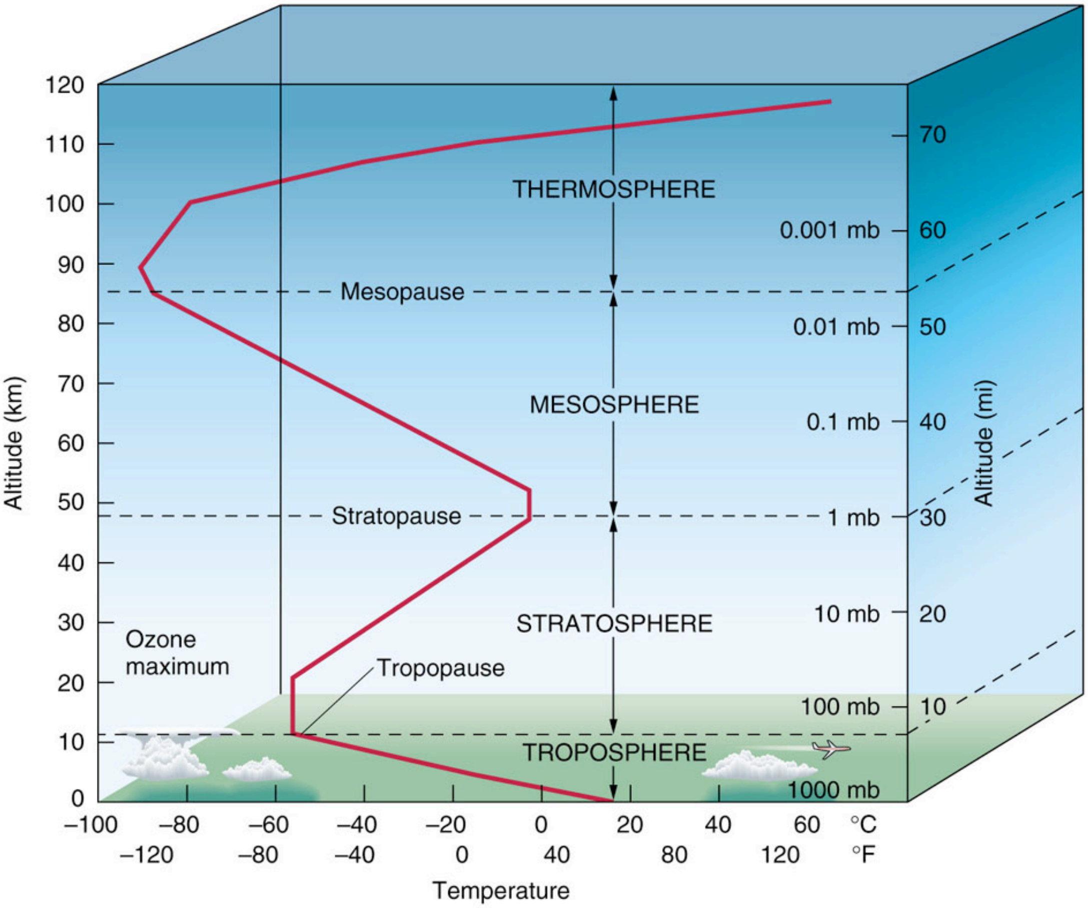

Figure 5 Vertical atmospheric temperature structure (source: robertcarrollweather)

10.2.1 Troposphere

The troposphere is the region of Earth's atmosphere from sea level to an altitude of 11 km (36,000 feet or 7 miles high). Nearly all of the weather that we are accustom to occurs in the troposphere (Figure 5). Thunderheads of large storms typically develop to a height of 25,000 to 30,000 feet. This region of the atmosphere is kept well stirred or mixed by rising and descending air currents. It is common for air molecules in the troposphere to circulate from Earth's surface to a height of 10 km in just a few days.

Air temperature in the troposphere decreases steadily from sea level to an altitude of 11 km. The decrease in air temperature is due primarily to the fact that sunlight warms the Earth's surface which in turn warms the air above it. The rate at which air temperature decreases with altitude is called the temperature lapse rate. The average lapse rate in the troposphere is about 6.5 ^{o}C for every 1,000 meters in altitude or about 3.6 ^{o}F per 1,000 feet. However, this rate changes with weather conditions. Air temperature stops decreasing with altitude at the top of the troposphere. From roughly 11 km to 20 km air temperature remains fairly constant at -60 to -80 ^{o}C (-76 to -112 ^{o}F).

10.2.2 Stratosphere

The stratosphere is the region of the atmosphere from 11 to 50 km. The boundary between the troposphere and stratosphere is called the tropopause. The height of the tropopause varies. It can be as high as 20 km near the equator and as low as 7 km over the poles. It also varies seasonally being higher in the summer than in the winter.

Beginning at 20 km, temperatures in the stratosphere increase with altitude producing a temperature inversion. The inversion prevents the vertical circulation and mixing of air in the troposphere from extending into the stratosphere. The inversion also minimizes the amount of vertical circulation and mixing that occurs in the stratosphere itself.

Commercial jet aircraft fly in the lower part of the stratosphere to avoid the turbulence which is common in the troposphere. However, air is roughly a thousand times thinner at the top of the stratosphere than at sea level. Because of this, aircraft and weather balloons reach their maximum operational altitudes in the lower part of the stratosphere. For example, the altitude record for sustained flight is held by the SR-71 Blackbird aircraft at 85,069 feet (25.9 km).

The ozone region (Figure 5) is a major cause of stratosphere temperature increasing with altitude. Ozone is a molecule consisting of three oxygen atoms with a symbol of O_3 . Ozone is formed in Earth's stratosphere as the result of solar ultraviolet light being absorbed by ordinary O_2 oxygen molecules. The absorbed energy splits an O_2 molecule into two individual oxygen atoms. Each of the oxygen atoms then combines with an unbroken O_2 molecule forming O_3 ozone. Even though ozone molecules in the stratosphere last for a long time, they are fundamentally unstable. Eventually an O_3 ozone molecule absorbs enough ultraviolet light to split it back into an O_2 oxygen molecule and an individual oxygen atom. In equation form

$$O_2 + hf \rightarrow 2O$$

$$O + O_2 \leftrightarrow O_3$$

where hf is an ultraviolet photon of light

h = Planck's constant, and

f = frequency

The stratosphere contains about 90 percent of the atmosphere's ozone. The ozone layer absorbs 97 to 99 percent of the Sun's medium frequency ultraviolet light (from about 200 nm to 315 nm) shielding Earth's inhabitants from the harmful effects of solar ultraviolet radiation. Due to the lack of vertical circulation, materials that get into the stratosphere can stay there for a long time. Such is the case with chemicals called CFCs (chlorofluorocarbons) which tend to destroy the ozone layer.

The ultraviolet energy absorbed in the process of forming and splitting ozone molecules is in part responsible for temperature in the stratosphere increasing with altitude. If ozone were not present, air in the stratosphere would probably become colder with increasing altitude as air does in the troposphere.

The stratosphere is very dry containing little water vapor. Because of this, few clouds form in the stratosphere. Nearly all clouds develop in the lower moist troposphere. An exception to this are polar stratospheric clouds (PSCs) which form in the lower stratosphere in poler regions during winter. They form at an altitude of 15 to 25 km when temperatures at that height drop below -78 ^{o}C.

10.2.3 Mesosphere

The mesosphere is the region of Earth's atmosphere stretching from about 50 to 85 km. Mesosphere means the middle sphere. It lies above the stratopause and below the mesosphere (Figure 5). The atmosphere is thin in the mesosphere resulting in very low atmospheric pressures ranging from 1 mb at the base to less than 0.01 mb in the upper part of the mesosphere. The mesosphere is also very dry preventing the formation of clouds. Temperature decreases with altitude in the mesosphere. The upper region of the mesosphere is the coldest part of the atmosphere. At an altitude of 85 km the temperature is about -100 ^{o}C (- 148 ^{o}F).

Most meteors vaporize in the mesosphere causing this layer to have relatively high concentrations of iron and other metallic atoms.

It is interesting to note that the mesosphere is the most difficult part of the atmosphere to study. Weather balloons and aircraft cannot fly high enough to reach the mesosphere. Satellites orbit above the mesosphere in the thermosphere and exosphere and thus cannot directly measure mesospheric conditions. Sounding rockets have been used to measure mesospheric characteristics, but such flights are very brief. Consequently, much about the mesosphere is still a mystery.

10.2.4 Thermosphere

The thermosphere extends above the mesosphere from roughly 85 to over 500 km in altitude (Figures 5 and 6). Air pressure in the thermosphere is very low, less than 0.001 mb, because there are so few atoms and molecules in this part of the atmosphere.

Temperature in the thermosphere increases with altitude from approximately –100 ^{o}C just above the mesosphere to a maximum in the upper part of the thermosphere. Temperature rises quickly at first and then tapers off becoming almost isothermic above 400 km (see Figure 6). Peak temperature is heavily dependent on solar activity varying from around 500 ^{o}C at solar minimum to over 2,000 ^{o}C during solar maximum. Even though this temperature is extremely high, a person shielded from the Sun would not sense the thermosphere as being hot. This is because there are too few molecules in this part of the atmosphere to transfer any meaningful amount of heat to anything that they may collide with, for example a person. Consequently, the thermosphere is very hot but feels cold.

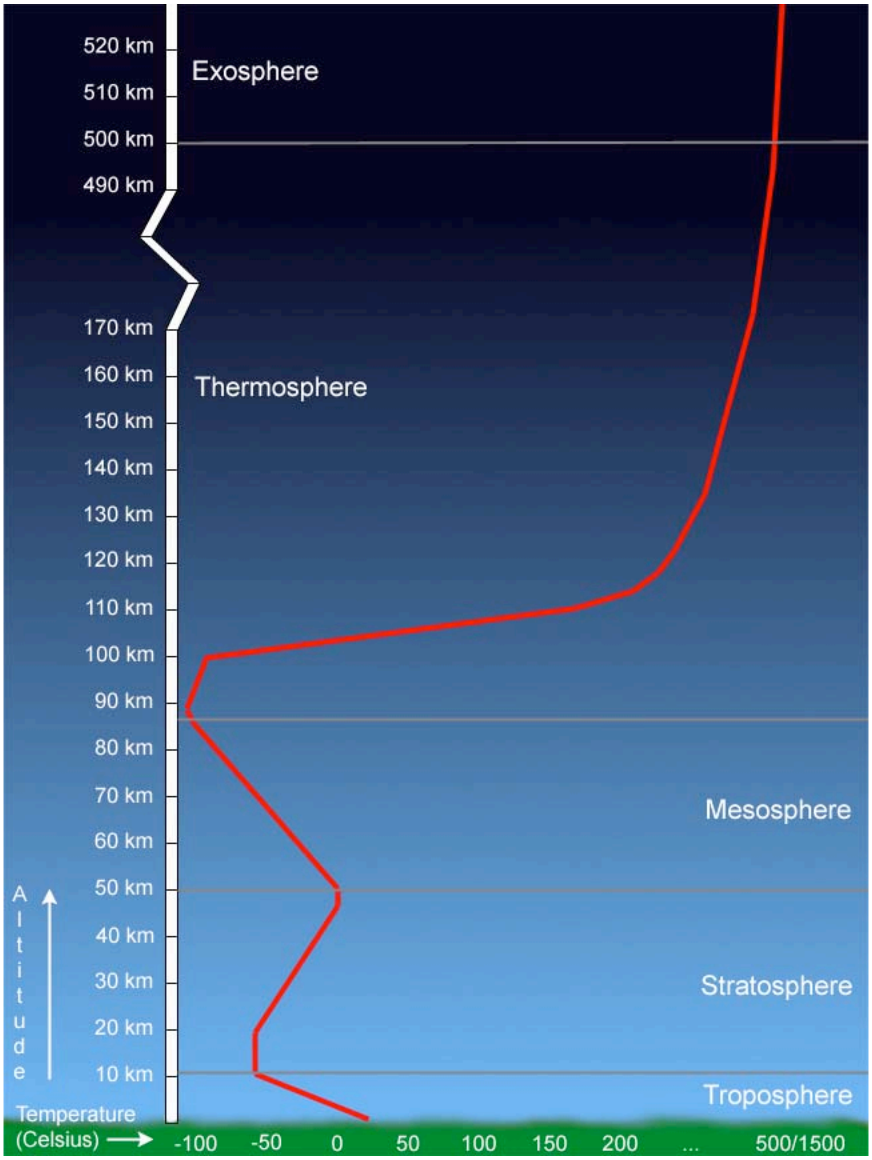

Figure 6 Earth's upper atmosphere (source: www.windows2universe.org)

Oxygen molecules (O_2), oxygen atoms (O), and nitrogen molecules (N_2) in the thermosphere absorb extreme ultra violate (EUV) energy from the Sun warming the air and accounting for the increase in temperature with altitude. There are so few atoms and molecules in the thermosphere that the absorption of a small amount of EUV energy produces a large increase in air temperature. The thermosphere is typically 200 ^{o}C hotter during the day than at night.

Low air density means that the collision rate between molecules in the thermosphere is very low. For example, an air molecule such as O_2 typically travels a kilometer before colliding with another molecule. In comparison, an oxygen molecule near Earth's surface moves only one millionth of a centimeter between collisions.

Below the thermosphere various species of air molecules are thoroughly mixed together by turbulence in the atmosphere. This is not the case in the thermosphere. Instead, molecules and atoms diffuse throughout the thermosphere. The force of gravity causes various types of atoms and molecules to become distributed throughout the thermosphere according to their atomic or molecular weight.

The thermopause is the top of the thermosphere marking the boundary between the thermosphere and the exosphere. The altitude of the thermopause varies considerably with the solar cycle. During solar minimum the altitude of the thermopause is around 500 km. Increasing levels of extreme ultra violate radiation during solar maximum heats the thermosphere raising the altitude of the thermopause to around 1,000 km.

10.2.5 Exosphere

The exosphere is the uppermost region of Earth's atmosphere. The bottom of the exosphere ranges in altitude from around 500 to 1,000 km as the thermosphere below it expands and contracts with the solar cycle. The exosphere gradually fades into the vacuum of space and thus does not have an explicit upper boundary. The air is so extremely thin in the exosphere that collisions between molecules rarely occur.

Many satellites, including the International Space Station (ISS) orbit within the thermosphere and exosphere. The ISS orbits in the thermosphere at an altitude of about 330 km. Although the atmosphere in the thermosphere and exosphere are very thin, there is still enough air to cause a slight drag on satellites orbiting in these regions. The drag eventually causes satellites to fall out of orbit burning up as they re-enter Earth's atmosphere.

10.3 Atmospheric Heat Loss

We saw above that sunlight heats the Earth's surface which in turn warms the air above it, providing the heat source for the troposphere. Absorption of solar ultra-violate light is responsible for the ozone process that heats the stratosphere. In the upper atmosphere absorption of solar x-ray and EUV energy heats the thermosphere. These are the major sources of heat that warm the atmosphere.

Radiation, particularly in the infra-red spectrum, is the principal mechanism of heat loss from the atmosphere. The thermal balance and temperature profiles of the upper atmosphere are also affected by processes of conduction and convection heat transport. For example, convection carries heat from the thermosphere into the mesosphere. While this represents a major loss of heat from the thermosphere, it is only a minor source of heat for the mesosphere. Thermal conduction is efficient in the thermosphere due to low pressures and the presence of free electrons resulting from EUV ionization of neutral atoms and molecules. Large thermal conductivity accounts for the isothermal characteristics of the thermosphere above 400 km, although thermospheric temperatures vary considerably over time. In Figure 6 the red temperature profile is nearly vertical above 400 km indicating that there is little change in temperature with altitude. Chemical transport of heat occurs when species of atoms and molecules are photoionized by EUV energy in one place and recombine back into neutral species somewhere else. For example, the mesosphere is heated in part by the recombination of atomic oxygen that was ionized in the thermosphere. Large scale winds can affect the horizontal distributions of temperatures in various regions of the atmosphere.

The balance between these processes produces the atmospheric temperature structures depicted in Figures 5 and 6.

10.4 Chemical Composition of the Atmosphere

The composition of Earth's atmosphere at sea level is shown in Figure 7. At sea level 78.08% of the atmosphere is composed nitrogen and 20.95% oxygen. All the other gases comprise only 0.97% of the atmosphere. Notice that at sea level concentrations of hydrogen (0.00005%) and helium (0.0005%) are negligible. However, in the thermosphere hydrogen and helium become the dominate gas molecules.

Composition of the atmosphere from sea level to roughly 50 km remains essentially the same as that shown in Figure 7 due to air currents constantly mixing atmospheric molecules. The situation gradually changes from 50 to100 km. Above 100 km mixing no longer occurs. Instead, molecules and atoms diffuse throughout the rarified thermosphere. As they diffuse the force of gravity causes various types of atoms and molecules to become distributed according to their atomic or molecular weight producing the distribution shown in Figure 8.

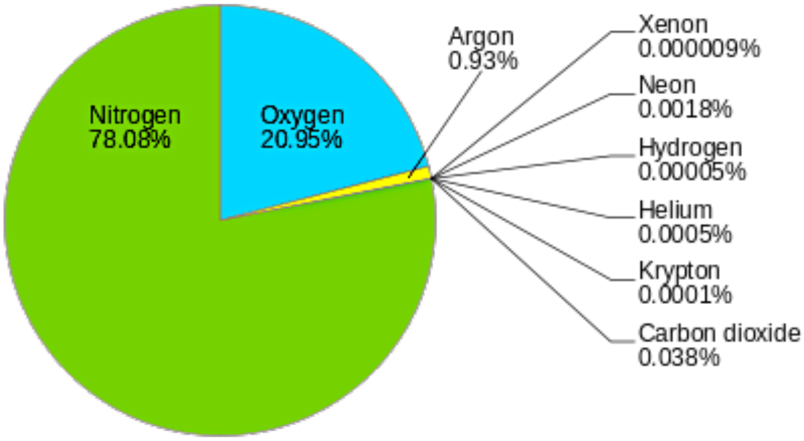

Figure 7 Composition of atmosphere at sea level (source: gaharceram.com)

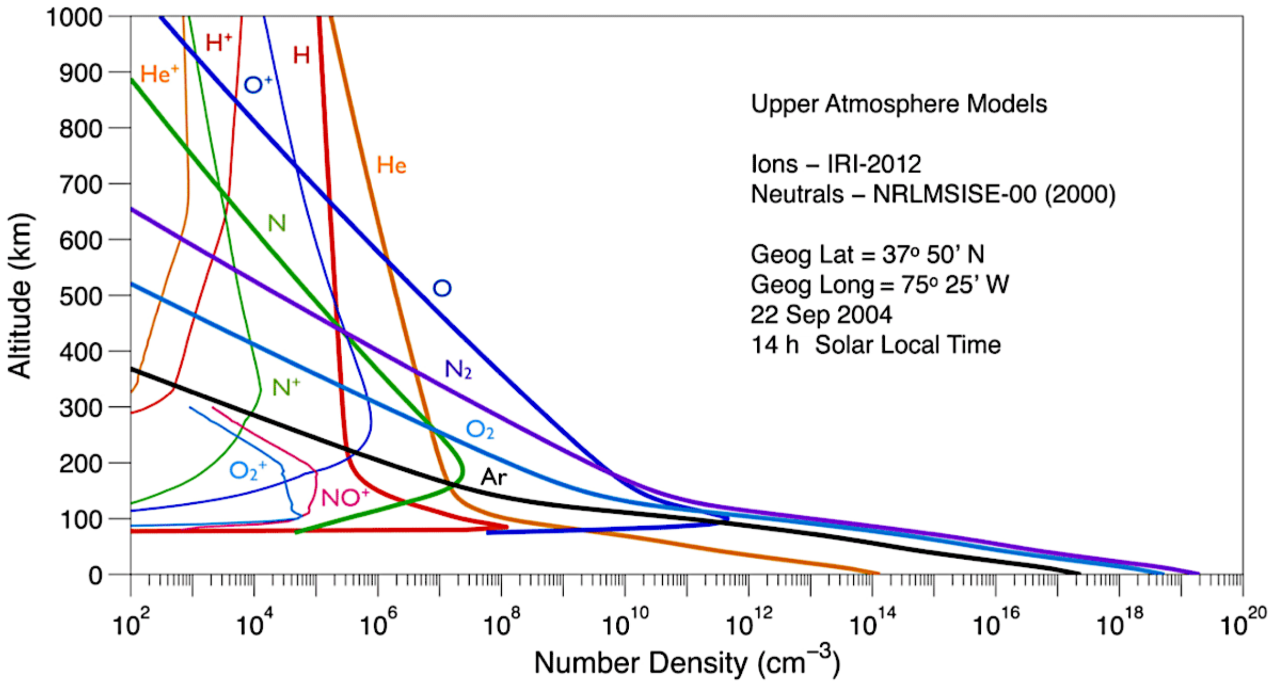

Figure 8 Chemical composition of the atmosphere (source: angeo.copernicus.org)

Molecular oxygen (O_2) is dissociated to atomic oxygen by solar ultra-violate radiation at wavelengths between 102.7 and 175.9 nm according to

$$O_2 + hf \rightarrow O + O$$

where

hf = a photon of ultra-violate radiation,
h = Planck's constant,
f = frequency of the ultra-violate radiation = $1/\lambda$
λ = wavelength

An increasing amount of atomic oxygen begins appearing above 90 km. At around 125 km equal concentrations of atomic (O) and molecular oxygen (O_2) are present. From 125 to ~ 600 km atomic oxygen dominates not only molecular oxygen but other species of atoms and molecules as well (Figure 8).

Molecular nitrogen (N_2) is not directly dissociated to the atomic form (N) in the atmosphere, though it does appear as a product of other reactions. This explains the higher concentration of atomic oxygen compared to atomic nitrogen in the upper atmosphere. However, the force of gravity is less on molecular nitrogen (N_2) due to its lower mass than molecular oxygen (O_2). Consequently, in Figure 8 molecular nitrogen N_2 is found at higher altitudes than molecular oxygen (O_2).

At an altitude of 600 to 700 km hydrogen and helium become the dominate species, as shown in Figure 8, due to their low mass. In contrast, only trace amounts of hydrogen and helium are present in the troposphere. Helium comes from radioactive decay in Earth's crust and diffuses up through the atmosphere eventually escaping into space. Atomic hydrogen is formed by the dissociation of water at an altitude around 100 km. It too diffuses upward and escapes into space. It is much more difficult for atomic oxygen and nitrogen to escape into space due to their much greater masses. However, significant quantities of atomic oxygen ions (O^+) in Earth's polar regions do escape into the magnetosphere creating the polar wind.

Minor species in the upper atmosphere include water, carbon dioxide, and oxides of nitrogen. While only trace amounts of water vapor are present, it nevertheless is important as a source of hydrogen. Its presence also causes ions to become hydrated at altitudes below the mesopause. Nitric oxide (NO) is important in the ionosphere D region chemistry as is carbon dioxide (CO_2).

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