Earth's Atmosphere Reading

Background

The atmosphere, where weather takes place, encircles the globe as a relatively thin envelope of gases and tiny, suspended particles. In fact, 99% of the atmosphere's mass is confined to a thin layer that in thickness is only about 0.25% of the Earth's diameter. Hence, the planet's atmosphere is comparable in thickness to the thin skin of an apple. Yet, the thin atmosphere skin is essential for life and the orderly functioning of physical and biological processes on Earth. The atmosphere shields against organisms from exposure to hazardous levels of ultraviolet radiation; it contains gases necessary for the life-sustaining processes of cellular respiration and photosynthesis; and it supplies the water needed by all forms of life.

Our current understanding of the atmosphere, weather, and climate is the culmination of centuries of painstaking inquiry by scientists from many disciplines. Physicists, chemists, astronomers, and others have applied basic principles in unlocking the mysteries of the atmosphere.

Evolution of the Atmosphere: *Primeval Phase*

Earth, as well as the sun and the entire solar system, is believed to have developed from an immense cloud of dust and gases within the Milky Way galaxy. The Earth's mass grew by accretion as the planet swept up cosmic dust in its path and its surface was bombarded by meteorites. In time, volcanoes began to spew forth huge amounts of lava, ash, and gases. By about 4.4 billion years ago, the planet's gravitational field was strong enough to retain a thin gaseous envelope, the Earth's primeval atmosphere.

The principle source of atmospheric gases was **outgassing**, the release of gases from rock through volcanic eruptions and impact of meteorites on the rocky surface of the planet. Perhaps as much as 85% of all outgassing took place within a million or so years of the planet's formation, but outgassing has persisted at a slower rate throughout the planet's existence.

Because of outgassing, the primeval atmosphere was mostly carbon dioxide (CO_2), with some nitrogen (N_2), and water vapor (H_2O), and trace amounts of methane (CH_4), ammonia (NH_3), sulfur dioxide (SO_2), and hydrochloric acid (HCl). Radioactive decay of an isotope of potassium in the planet's bedrock added argon (Ar), an inert (chemically nonreactive) gas, to the evolving atmosphere. Free oxygen (O or O_2) was absent, although oxygen was combined with other elements in various chemical compounds such as carbon dioxide.

The Earth's CO_2 rich atmosphere was perhaps 10 to 20 times denser than the present atmosphere. Some scientists suggest that between 4.5 and 2.5 billion years ago, the sun was only about 75% as bright as it is today. This did not mean a cooler planet, however, because of the abundance of CO_2. As mentioned earlier, carbon dioxide slows the escape of the Earth's heat to space. In fact, numerical models that simulate this early atmosphere predict average surface temperatures as high as 85 to 110ºC (185 to 230 F).

By about 4 billion years ago, the planet cooled enough that the outgassed water vapor began condensing into clouds, and rains gave rise to the first oceans that eventually covered perhaps 95% of the planet's surface. These rains were key to a marked decline in the concentration of atmospheric CO_2. Carbon dioxide dissolved in rainwater produces weak carbonic acid that reacts chemically with the bedrock. The net effect of this large-scale geochemical process was more carbon chemically locked in rocks and minerals and less CO_2 in the atmosphere.

Living organisms also played an important role in the evolving atmosphere, primarily through **photosynthesis**, the process whereby plants use sunlight, water, and carbon dioxide to manufacture their food. A byproduct of this process is oxygen (O_2). Hence, plants are a *sink* for carbon dioxide and a *source* of oxygen. Although photosynthesis dates back to at least 2.5 billion years ago when the first primitive forms of life (blue-green algae) appeared in ancient seas, it is unlikely that photosynthesis was an important player in the atmosphere’s evolution until about 2 billion years ago.

Photosynthesis was far less important than geochemical processes in removing carbon dioxide from the atmosphere. Prior to about 2 billion years ago, most oxygen produced via photosynthesis combined with ocean sediments and very little entered the atmosphere. By about 2 billion years ago, oxidation of ocean sediments had tapered off and photosynthetically produced oxygen began cycling into the atmosphere. With the concurrent decline in CO_2, within 500 million years, oxygen (O_2) became the second most abundant atmospheric gas after nitrogen (N_2).

Oxygen emerged as a major component of the Earth’s atmosphere, and the ozone shield formed. This shield is formed when solar ultraviolet radiation powers reactions that convert oxygen to ozone (O_3) and vice versa. In this way potentially lethal intensities of UV radiation did not reach the Earth’s surface, making it possible for terrestrial forms of life to emerge.

Although carbon dioxide has been a minor component of the atmosphere for at least the past 3.5 billion years, from time to time in the geologic past its concentration fluctuated with important implications for climate. All other factors being equal, more CO_2 in the atmosphere means higher temperatures at the Earth’s surface. Geological evidence points to a burst of volcanic activity on the Pacific ocean floor about 100 to 200 million years ago. Some of the CO_2 released during that activity eventually found its way to the atmosphere and raised global temperatures by as much as 10 ºC. During the Ice Age, also, atmospheric carbon dioxide levels fluctuated, decreasing during episodes of glacial expansion and increasing during episodes of glacial recession.

Evolution of the Atmosphere: *Modern Phase*

Ultimately, these gradual evolutionary processes produced the modern atmosphere, which is a mixture of many different gases. Because the lower atmosphere continually circulates and mixes, the principal atmospheric gases occur almost everywhere in the about the same relative proportions up to an altitude of about 80km. Above 80 km, gases are stratified (layered) such that concentrations of the heavier gases decrease more rapidly with altitude than do concentrations of the lighter gases.

Nitrogen and oxygen are the chief gases of the atmosphere. Not counting water vapor (which has a high variable concentration), nitrogen (N_2) occupies 78.08% by volume and oxygen 20.95%. The next most abundant gases are argon (0.93%) and carbond dioxide (0.035%). The atmosphere also contains small quantities of helium (He), methane (CH_4), hydrogen (H_2), ozone (O_3), and several other gases. See Figure 1

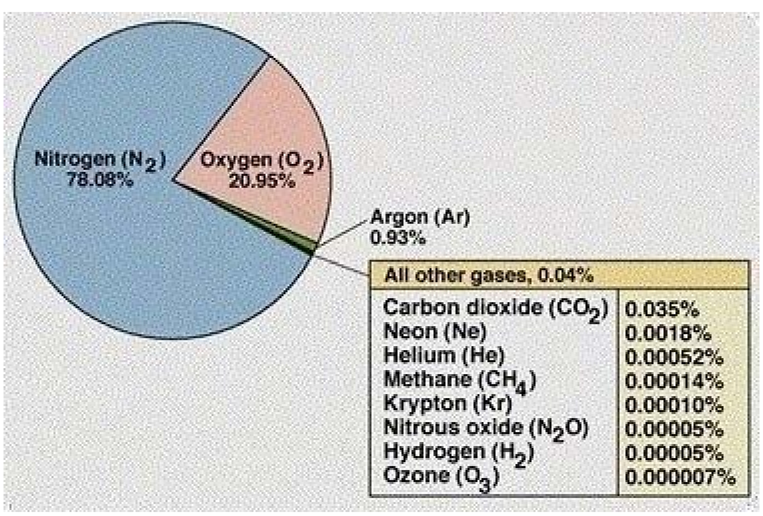

Figure 1. Gas Composition of Earth's Atmosphere

In addition to gases, the Earth’s atmosphere contains minute liquid and solid particles, collectively called **aerosols**. Some aerosols-water droplets and ice crystals- are visible as clouds. Others are too small to be visible. Most aerosols occur in the lower atmosphere near their source, the Earth’s surface. They originate through forest fires, from wind erosion of soil, as tiny sea-salt crystals from ocean spray, in volcanic emissions, and from industrial and agricultural activities. Also, some aerosols, such as meteoric dust, enter the atmosphere from above.

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It may be tempting to dismiss as unimportant because substances that make up only a small fraction of the atmosphere, but the significance of an atmospheric gas or aerosol is not necessarily related to its relative abundance. For example, water vapor, carbon dioxide, and ozone (O3) occur in minute concentrations, yet they are essential for life. By volume, no more than about 4% of the lowest kilometer of the atmosphere is water vapor- even in the warm, humid air over tropical oceans and rainforests. Without water vapor, however, there would be no clouds, and nor rain or snow to replenish soil moisture, rivers, lakes, and seas. Although comprising only 0.035% of the upper atmosphere, carbon dioxide is essential for photosynthesis. Furthermore, water vapor and carbon dioxide act as a blanket over the Earth’s surface, causing the lower atmosphere to retain heat and making the planet warmer and more amenable to life. Although the volume percentage of ozone is minute, this vital gas shields organisms, including ourselves from exposure to potentially lethal intensities of ultraviolet radiation from the sun.

The aerosol concentration of the atmosphere is also relatively small, yet these suspended particles participate in important processes. Some aerosols act as nuclei for the development of clouds and precipitation, and some influence air temperature by interacting with solar radiation.

Temperature Profile of the Atmosphere

For convenience of study, the atmosphere is subdivided into concentric layers based upon the vertical profile of the average air temperature, as shown in Figure 2. Almost all weather occurs within the lowest layer, the **troposphere**, which extends from the Earth’s surface to an average altitude ranging from about 6 km (3.7 mi) at the poles to about 16 km (10 mi) at the equator. Normally, but not always, the temperature within the troposphere decreases with increasing altitude. Hence, the air temperature is usually lower on mountaintops than in surrounding lowlands. On average within the troposphere, the temperature falls 6.5 degrees Celsius per 1000 meters. The upper boundary of the troposphere, called the **tropopause**, is a transition zone between the troposphere and the next higher layer, the stratosphere.

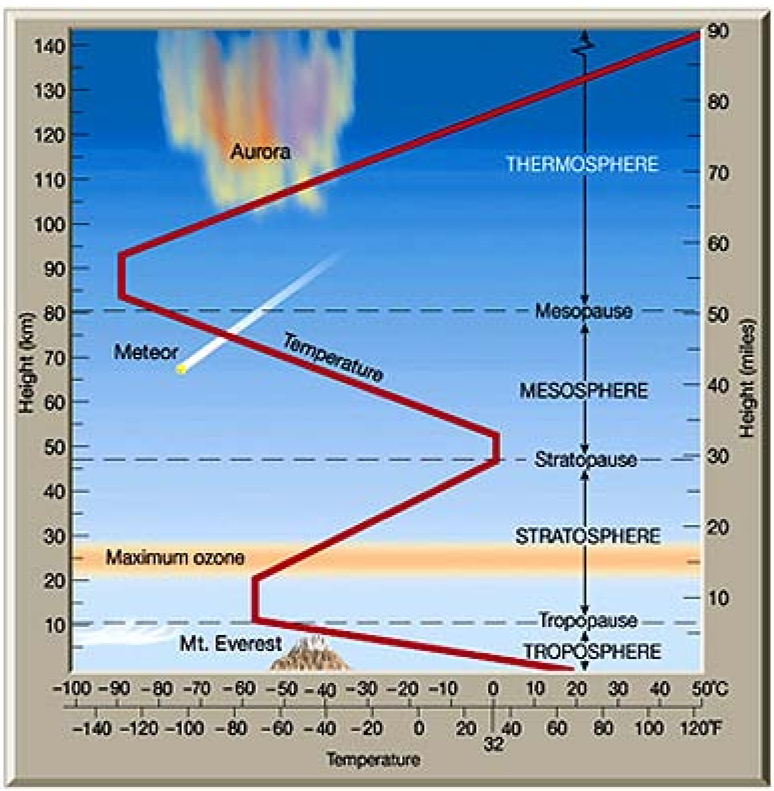

Figure 2. Average Variation of Temperature with Altitude

The **stratosphere** extends from the tropopause to about 50km. On average, in the lower portion of the stratosphere, the temperature does not change with altitude. When temperature is constant, the condition is described as isothermal. Above about 20km, the temperature rises with increasing altitude up to the top of the stratosphere, the **stratopause**. At the stratopause, the temperature is not much lower than at sea level.

The stratosphere is ideal for jet aircraft travel because it is above the weather. Therefore, it offers excellent visibility and features generally smooth flying conditions. Since the early 1970s, however, scientists have been concerned about possible detrimental effects of certain air pollutants that enter the stratosphere. Because little air exchange takes place between the troposphere and the stratosphere, pollutants that reach the lower stratosphere may remain there for long periods. Gases and aerosols thrown into the stratosphere during violent volcanic eruptions, for example, can persist there for many months to years and perhaps trigger changes in climate. Other pollutants are eroding the protective ozone layer within the stratosphere.

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Chemical reactions, activated by the absorption of ultraviolet radiation from the sun, lead to the establishment and maintenance of a layer of ozone (O_3) within the upper stratosphere. The ozone layer absorbs most of the sun’s ultraviolet (UV) radiation, resulting in increased temperatures in this region of the stratosphere. UV absorption by ozone shields the Earth’s surface from excessive amounts of radiation.

The **stratopause** is the transition zone between the stratosphere and the next higher layer, the mesosphere. Within this layer, the temperature once again falls with increasing altitude. The mesosphere extends up to the mesopause, which is about 80km above the Earth’s surface and features the lowest average temperature in the atmosphere. Above this is the thermosphere, where temperatures at first are isothermal and then rise rapidly with altitude. Within the thermosphere, temperature is more variable with time than in any other region of the atmosphere.

The Ionosphere and the Aurora

The ionosphere is located primarily within the thermosphere, between altitudes of 80 and 400 km. The region is named for its relatively high concentration of ions. An ion is an atomic scale particle that carries an electrical charge. High-energy solar radiation entering the upper atmosphere strips electrons from oxygen and nitrogen atoms and molecules and leaves them as positively charge ions. The highest concentration of ions is in the lower portion of the thermosphere.

Although conditions in the upper atmosphere do not greatly influence day-to-day weather, the ionosphere is important for long-distance radio transmission. The ionosphere reflects radio signals. Radio signals travel in straight lines and bounce back and forth between the Earth’s surface and the ionosphere. By repeated reflections, a radio signal may travel completely around the globe.

The ionosphere is also the site of the spectacular aurora borealis (northern lights) in the Northern Hemisphere and the aurora australis (southern lights) in the Southern Hemisphere. Auroras appear in the night sky as overlapping curtains of greenish-white light, occasionally, fringed with pink. The bottom of the curtains is at an altitude of about 100km and the top is at 400km or higher.

An aurora is triggered by the solar wind, a stream of electrically charged subatomic particles (protons and electrons) that continually emanates from the sun and travels into space at speeds of 400 to 500 km per second. The Earth’s magnetic field deflects the solar wind and, as a consequence, is deformed into a teardrop-shaped cavity surrounding the planet known as the magnetosphere.

Earth’s Atmosphere vs. Other Planets

The Earth’s nitrogen/oxygen-dominated atmosphere is in striking contrast to the carbon-dioxide-rich atmospheres of neighboring planets Venus and Mars. The atmosphere of Venus is almost 100 times denser than the Earth’s atmosphere and features an average surface temperature of about 475 ºC. The Martian atmosphere, on the other hand, is much thinner than the Earth’s atmosphere and has average surface temperature of about -53 ºC. This contrast occurs even though all three planets likely started out with very similar atmospheres. The atmospheres of Earth, Mars, and Venus evidently followed different evolutionary paths.

The Martian Atmosphere

Sensors aboard NASA’s unmanned Mariner and Viking spacecraft confirmed suspicions that the Martian atmosphere differs considerably from the Earth’s atmosphere. The Martian atmosphere is 95% carbon dioxide, 2% to 3% nitrogen, 1% to 2% argon, and 0.1% to 0.4% oxygen. In addition, the Martian atmosphere is much thinner; its surface pressure is only 0.7% of Earth's average sea-level air pressure.

Outgassing produced the primeval atmospheres of both Earth and Mars. Gases were released from ancient planetary rock through volcanic eruptions and though impact when meteorites collided with the rocky surfaces of the planets. The gases were probably the same because the source rocks on both planets were chemically the same. Rock chemistry depends on the temperature at which crystallization takes place, which in turn depends on the planet's distance form the sun. Mars's greater distance form the sun (about 50% farther than Earth) would not produce significantly different crystallization (rock-forming) conditions. Hence, though outgassing, the primeval atmospheres of both planets were mostly carbon dioxide along with some nitrogen and water vapor- the principal gaseous emissions of volcanoes, both ancient and modern.

As noted elsewhere in this chapter, geochemical processes plus photosynthesis gradually altered the Earth's primeval atmosphere so that eventually nitrogen and oxygen became the principal gases and carbon dioxide was reduced to a minor component. From the beginning, however, carbon dioxide has remained the chief gaseous constituent of the Martian atmosphere, although its concentration has declined significantly.

Contrasts in the volcanic histories of Earth and Mars may help to explain why the atmospheres of the two planets evolved differently. On Mars, the bulk of volcanic activity apparently took place during the planet's first 2 billion years, whereas on Earth, volcanism has been more or less continuous throughout the planet's history. The decline volcanism on Mars cut the supply of nitrogen, and much of the original nitrogen escaped Mars's relatively weak gravitational field. Gravity, the force that holds the atmosphere to a planet, is about 38% weaker on Mars than on Earth. This is because Mars is smaller and less massive.

The decline in Martian volcanism also meant less CO_2 released to the atmosphere. At the same time, other geological processes reduced the density of the Martian atmosphere by removing carbon dioxide. Some CO_2 adhered to the fine sediment that blankets the planet's surface, and some carbon dioxide became locked up in carbonate rocks.

Evidence that Mars was warmer and wetter about 4 billion years ago than it is now appears to support the notion that the concentration of CO_2 declined. Carbon dioxide slows the loss of the planet's heat to space, so that as CO_2 thins, more heat escapes and temperatures on the surface of the planet fall. Perhaps 4 billion years ago, temperatures on the Martian surface were so high that water was liquid. The Mariner spacecraft photographed valleys that were cut by ancient rivers. Yet today, the mean temperature on the Martian surface is about -53 ºC much too slow for running water.

In 1994 S. W. Squyres of Cornell University and J.F. Kasting of Pennsylvania State University questioned the assumption that in the beginning Mars was much warmer and wetter than it is today. They argued that Mars was considerably colder than has been previously assumed. As pointed out elsewhere in this chapter, at the time the sun was about 75% as bright as it is today. Mars's greater distance from the sun compared to Earth would only exacerbate the cooling and there wasn't enough CO_2 in the Martian atmosphere to offset the cooling. Furthermore, Squyres and Kasting proposed that it was cold enough to form clouds of CO_2 ice crystals that reflected away sunlight, further adding to the cooling. What then explains running water on Mars?

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According to Squyres and Kasting, one possibility is that water flowing in the valleys did not originate as runoff from precipitation. Rather, water seeped out of the ground where it was kept from in the liquid state by the slowly cooling but still very hot interior of Mars. Explaining how the water was kept from freezing while flowing on the surface is more of a challenge. One possibility is that the Martian atmosphere contained some methane and/or ammonia, gases that have the same warming effect as CO_2. The combined heat-trapping by these gases may have kept the surface just warm enough for running water to remain liquid.

Scientists have reconstructed the formation of two curious features in the northern ice cap of Mars—a chasm larger than the Grand Canyon and a series of spiral troughs—solving a pair of mysteries dating back four decades while finding new evidence of climate change on Mars.

In a pair of papers published in the journal Nature on May 27, Jack Holt and Isaac Smith of The University of Texas at Austin’s Institute for Geophysics and their colleagues describe how they used radar data collected by NASA’s Mars Reconnaissance Orbiter to reveal the subsurface geology of the red planet’s northern ice cap. On Earth, large ice sheets are shaped mainly by ice flow. But on Mars, according to this latest research, other forces have shaped, and continue to shape, the polar ice caps.The northern ice cap is a stack of ice and dust layers up to two miles (three kilometers) deep covering an area slightly larger than Texas. Analyzing radar data on a computer, scientists can peel back the layers like an onion to reveal how the ice cap evolved over time.

In summary, the difference in evolutionary paths taken by the atmospheres of Earth and Mars may be due largely to physical contrasts between the two planets. The Earth has been more volcanically active and is more massive than Mars.