The Earth's Atmosphere

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We live at the bottom of a swirling ocean of air – Thunderstorms brewing in the Pacific Ocean

1. IN PERSPECTIVE

Our atmosphere is a delicate life-giving blanket of air that surrounds the fragile Earth. The Earth with no atmosphere would have no lakes or oceans, there would be no sounds no clouds, no red sunsets. It would be unimaginably cold at night and unbearably hot during the day. All things on Earth would be at the mercy of an intense Sun beating down upon the planet.

We have adapted so completely to our environment of air that we sometimes forget how truly remarkable this substance is. Even though the air is tasteless, odourless and most of the time invisible, it yet 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 the air, it might seem surprising that between your eyes and this page, there are trillions of air molecules. Some of these may have been in a cloud only yesterday, over another continent last week or perhaps in the breath of a very famous person who lived hundreds of years ago.

2. OVERVIEW OF THE EARTH'S ATMOSPHERE

The universe contains billions of galaxies and each galaxy is made up of billions of stars. Stars are hot glowing balls of gas that generate energy by converting hydrogen into helium near their centres.
Our Sun is an average sized star situated near the edge of the Milky Way galaxy. Revolving around the Sun is the Earth and 8 other planets, if we count Pluto (see figure 1).

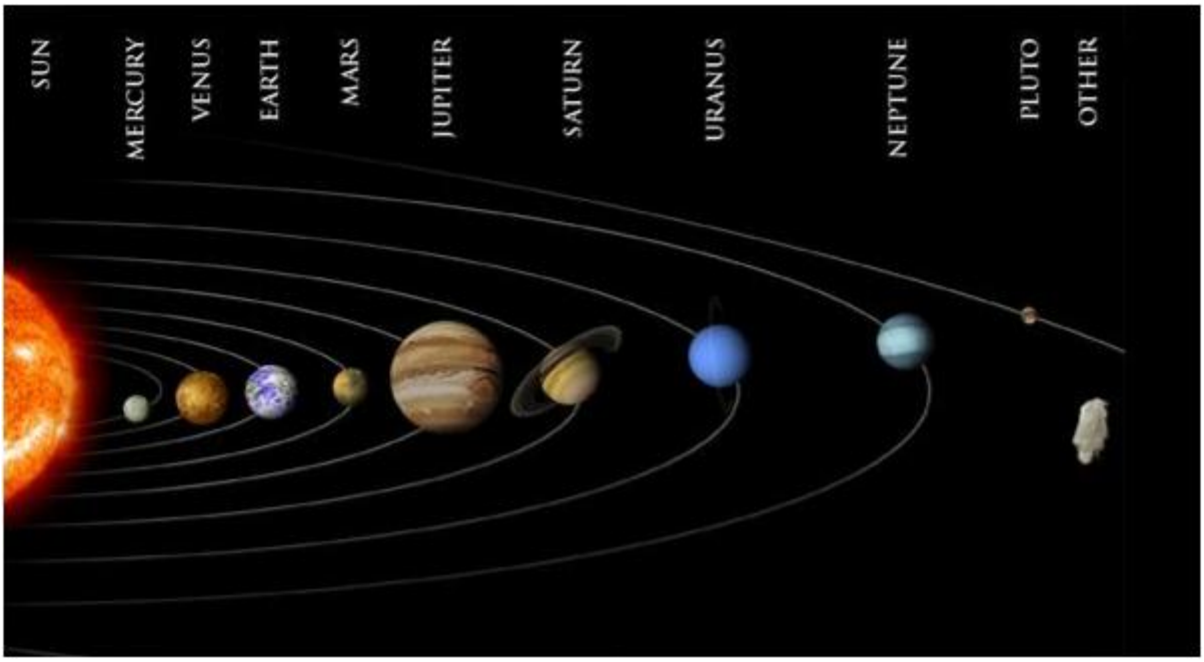

Figure 1: Positions of planets in our Solar System

These planets, along with a host of other materials (comets, asteroids, meteors) comprise our Solar System.
Warmth for these planets is provided primarily by the Sun's energy. At an average distance of 150 million kilometres (93 million miles), the Earth intercepts only a very small fraction of the Sun's total energy output. However this radiant energy (or *radiation*)[1] that drives the atmosphere into patterns of everyday wind or weather allows the Earth to maintain an average surface 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 to above 50°C (122°F) during an oppressively hot desert day!

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[1] Radiation is energy transferred in the form of waves that have electrical and magnetic properties. For example, the light that we see is radiation.

The Earth's **atmosphere** is a thin gaseous envelope comprised mostly of nitrogen and oxygen with small amount of other gases, such as carbon dioxide and water vapour. Nested in the atmosphere are clouds of liquid water and ice crystals.

The thin blue area in Figure 2 below represents the densest part of the atmosphere.

Figure 2: Earth's atmosphere as seen from space

Although our atmosphere extends upwards for many hundreds of kilometres, 99% of the atmosphere lies within a mere 30 kilometres (19 miles) of the Earth's surface. This thin blanket of air consistently shields its inhabitants from the Sun's dangerous ultraviolet radiant energy as well as the onslaught of material from interplanetary space. There is no definite upper limit to the atmosphere, rather it becomes thinner and thinner and eventually merges with empty space which surrounds all the planets.

2.1. Composition of the atmosphere

2.1.1. Composition table

The table below shows the various gases present in a volume of air near the earth's surface.

Gas / Particles	Symbol	% per volume	Parts per million (ppm)
Nitrogen	N_2	78.08	-
Oxygen	O_2	20.95	-
Argon	Ar	0.93	-
Neon	Ne	0.0018	-
Helium	He	0.0005	-
Hydrogen	H	0.00006	-
Xenon	Xe	0.000009	-
Water vapour	H_2O	0 to 4	-
Carbon dioxide	CO_2	0.036	365[2]
Methane	CH_4	0.00017	1.7
Nitrous oxide	NO_2	0.00003	0.3
Ozone	O_3	0.000004	0.04[3]
Dust, soot	-	0.000001	0.01 to 0.15
Chlorofluorocarbons	CFCs	0.00000002	0.0002

2.1.2. Preponderance of Nitrogen and Oxygen

Notice that **nitrogen** (N_2) occupies about 78% and **oxygen** (O_2) about 21% of the total volume. If all other gases are removed, these percentages for nitrogen and oxygen hold fairly constant up to an elevation of about 80 km (about 50 miles).

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 where organic matter decays and when oxygen combines with other substances to form oxides. It is also taken from the atmosphere during breathing, as the lungs take in oxygen and release carbon dioxide (CO_2). The addition of oxygen to the atmosphere occurs during *photosynthesis*, as plants, in presence of sunlight, combine carbon dioxide and water to produce sugar and oxygen.

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[2] *It means that there are 365 molecules of CO2 for every million air molecules.*
[3] *Stratospheric values are about 5 to 12 ppm.*

2.1.3. Water vapour

The concentration of the invisible gas **water vapour** (H_2O), however, varies greatly from place to place and from time to time. Close to the surface in warm, steamy, tropical locations, water vapour may accounts for up to 4% of the atmospheric gases, whereas in colder arctic areas, it concentration may dwindle to a mere fraction of a percent. Normally invisible, water vapour molecules become visible only they transform into larger liquid or solid particle, such as cloud droplet or ice crystals.

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.

Water vapour is an *extremely* important gas in our atmosphere. Not only does it form into liquid and solid cloud particles that grow in size and fall to the Earth as precipitation, but it also releases large amounts of heat (called *latent heat*) when it changes from vapour into liquid water or ice. Latent heat is an important source of atmospheric energy, especially for storms, such as thunderstorms and hurricanes. Moreover, water vapour is a potent *greenhouse gas* because it absorbs a portion of the Earth outgoing radiant energy. Thus, water vapour plays a significant role in the Earth's heat-energy balance.

2.1.4. Carbon dioxide

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

The figure below reveals that the atmospheric concentration of CO_2 has risen more than 15% since 1958 when it was first measured at Mauna Loa Observatory in Hawaii.

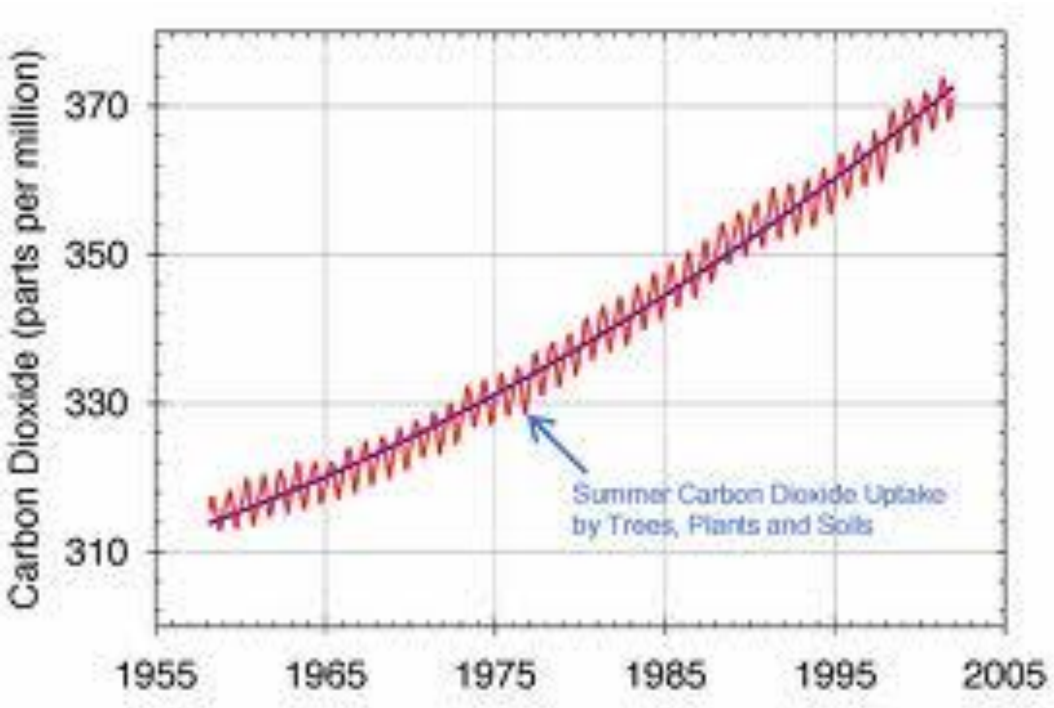

Figure 3: Carbon dioxide concentration increase with time

This increase means that CO_2 is entering the atmosphere at a greater rate than it is removed. It appears to be mainly due 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 to 20% of the observed increase.

Measurements of CO_2 also come from ice cores. In Greenland and Antarctica, for example, tiny bubbles trapped within the ice sheets reveal that, before the industrial revolution, CO_2 levels were stable at about 280 ppm. Since the early 1800s, however, CO_2 have increased by as much as 25%. With CO_2 levels presently increasing by about 0.4% per year, (1.5 ppm/year), scientist now estimate that the concentration of CO_2 will likely to a value near 500 ppm toward the end of the 21st century.

Carbon dioxide is another important greenhouse gas because, like water vapour, 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 and 6°F) by the year 2100.

Such warming (as we will learn in the final chapter 'The Earth's changing climate') could result in a variety of circumstances, such as increasing precipitations in certain areas and reducing it in others as the global air currents that steer the major storm systems across the Earth begin to shift from their 'normal' paths.

2.1.5. Other greenhouse gases

Carbon dioxide and water vapour are not the only greenhouse gases. Recently, others have been gaining notoriety, primarily because they, too, are becoming more concentrated. Such gases include *methane* (CH_4), *nitrous oxide* (NO_2) and *chlorofluorocarbons* (CFCs)[4].

Levels of methane, for example, have been rising over the past century, increasing by about 0.5% per year. Most methane appears to derive from the breakdown from plant material by certain bacteria in rice paddies, wet oxygen-poor soil, the biological activity of termites and the biochemical reactions in the stomachs of cows. Just why methane should be increasing so rapidly is currently under study.

Levels of nitrous oxide (commonly known as laughing gas) have been rising annually at the rate of about 0.25%. Nitrous oxide forms in the soil through a chemical process involving bacteria and certain microbes. Ultraviolet light from the Sun destroys it.

Chlorofluorocarbons represent a group of greenhouse gases that also have been increasing in concentration. These have been the most widely used propellants in spray cans. Today, however, they are mainly used as refrigerants, as propellants for the blowing of plastic-foam insulation and as solvents for cleaning electronic microcircuits. Although their average concentration in a volume is quite small, they have an important effect on our atmosphere as they not only have the potential of raising global temperatures but they also play a part in destroying the ozone gas in the stratosphere.

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[4] *Because these gases (including CO_2) occupy only a small fraction of a percent of a volume of air near the surface, they are referred to collectively as traces gases.*

2.1.6. Ozone

At the surface, **ozone** (O_3) is the primary ingredient of *photochemical smog*[5], which irritates the eyes and throat and damages vegetation. But the majority of atmospheric ozone (about 97%) is in the stratosphere where it is formed naturally as oxygen atoms combine with oxygen molecules. Here the concentration of ozone averages less than 0.002% by volume. This small amount is important however because it shields plants, animals and humans from the Sun's harmful ultraviolet rays. It is ironic that ozone, which damages plant life in a polluted environment, provides a natural protective shield in the upper atmosphere so that plants on the surface may survive. We will see in chapter ... that, when CFCs enter the stratosphere, ultraviolet rays break them apart and the CFCs release chlorine destroying ozone. A single CFC molecule can destroy 100,000 ozone molecules. Chlorine is a catalyst for ozone destruction. It is restored to its initial state once it has completed its reaction, so it can destroy ozone molecules again.

Because of this effect, ozone concentration in the stratosphere had been decreasing over parts of the Northern and Southern hemispheres. The reduction in stratospheric ozone levels over springtime Antarctica had plummeted to such an alarming rate that, during September and October, there is an *ozone hole* over the region.

Entered in force in January 1989, the Montreal Protocol now protects the ozone layer by phasing out the production of numerous substances believed to be responsible for ozone depletion.

In October 2012, NASA and National Oceanic and Atmospheric Administration (NOAA) satellites data reported that the average area covered by the Antarctic ozone hole in 2012 was the second smallest in the last 20 years. Atmospheric ozone is no longer declining because concentrations of ozone-depleting chemicals stopped increasing and are now decreasing.

[5] *Originally the word smog came from the combination of smoke and fog. Today, however, it usually refers to the type of air pollution that forms in large cities when chemical reactions take place in the presence of sunlight.*

2.1.7. Aerosols

Impurities from both natural and human sources are also present in the atmosphere. Wind picks up dust and soil from the Earth's surface and carries them aloft; small saltwater drops from ocean waves are swept into the air (upon evaporating, these drops leave microscopic salt particles suspended in the atmosphere); smoke from forest fires is often carried high above the Earth; and volcanoes spew many tons of fine ash particles and gases into the air.

Figure 4: Volcanic ash cloud

Collectively, these tiny solid or liquid suspended of various composition are called **aerosols**.

2.1.8. Pollutants

Some natural impurities found in the atmosphere are quite beneficial. Small, floating particles, for instance, act as a surface on which water vapour condenses to form clouds. However, most human impurities (and some natural ones) are a nuisance, as well as a health hazard. These are called **pollutants**. For example, car engines emit copious amounts of *nitrogen dioxide* (NO_2), *carbon monoxide* (CO) and *hydrocarbons*. In sunlight, nitrogen dioxide reacts with hydrocarbons and other gases to produce ozone. Carbon monoxide is a major pollutant of city air. Colourless and odourless, this poisonous gas forms during the incomplete combustion of carbon-containing fuel. Hence, over 75% of carbon monoxide in urban areas comes from road vehicles.

The burning of sulphur-containing fuels (such as coil and oil) releases the colourless gas *sulphur dioxide* (SO_2) into the air. Then the atmosphere in sufficiently moist, the SO_2 may transform into tiny dilute drops of sulphuric acid. Rain containing sulphuric acid corrodes metals and painted surfaces and turns freshwater acidic. Acid rain (discussed in chapter ...) is a major environmental problem, especially downwind from major industrial areas. In addition, high concentrations of SO_2 produce serious respiratory problems in humans, such as bronchitis and emphysema (long-term, progressive disease of the lungs that primarily causes shortness of breath) and have an adverse effect on plant life.

2.2. The early atmosphere

The Earth's first atmosphere (some 4.6 billion years ago) was most likely made of *hydrogen* and *helium* (the 2 most abundant gases found in the universes), as well as hydrogen compounds, such as methane and ammonia. Most scientists feel that this early atmosphere escaped into space from the Earth's hot surface.

A second, more dense atmosphere, however, gradually enveloped the Earth as the gases from molten rock within its hot interior escaped through volcanoes and steam vents. We assumed that volcanoes spewed out the same gases as they do today: mostly water vapour (about 80%), carbon dioxide (about 10%) and a few percent of nitrogen. These gases (mostly water vapour and carbon dioxide) probably created the Earth's second atmosphere.

As millions of years passed, the constant outpouring of gases from the hot interior (known as *outgassing*) provided a rich supply of water vapour, which formed into clouds[6]. Rain fell upon the Earth for many thousands of years, forming the rivers, lakes and oceans of the world. During this time, large amounts of CO_2 were dissolved in the oceans. Through chemical and biological processes, much of the CO_2 became locked up in carbonate sedimentary rocks, such as limestone. With much of the water vapour already condensed and the concentration of CO_2 dwindling, the atmosphere gradually became rich in nitrogen (N_2), which is usually not chemically active.

It appears the oxygen (O_2), the second most abundant gas in today's atmosphere, probably began an extremely slow increase in concentration as energetic rays from the Sun split water vapour ((H_2O) into hydrogen and oxygen during a process called *photodissociation*. The hydrogen, being lighter, probably rose and escaped into space, while the oxygen remained in the atmosphere.

This slow increase in oxygen may have provided enough of this gas for primitive plants to evolve, perhaps 2 to 3 billion years ago. Or the plants may have evolved in an almost oxygen-free (anaerobic) environment. At any rate, plant growth greatly enriched our atmosphere with oxygen. The reason for this enrichment is that, during photosynthesis, plants, in the presence of sunlight, combine carbon dioxide and water the produce oxygen. Hence, after the plants evolved, the atmospheric oxygen content increased more rapidly, probably reaching its present composition about several hundred million years ago.

BRIEF REVIEW 1

- The Earth's atmosphere is a mixture of many gases. In volume, near the surface, nitrogen (N_2) occupies about 78% and oxygen (O_2) about 21%.
- Water vapour can condense into liquid cloud droplets or transform into delicate ice crystals. Water is the only substance in our atmosphere that is naturally found as a gas (water vapour), as a liquid (water) and as a solid (ice).
- Both water vapour and carbon dioxide (CO_2) are very important greenhouse gases.
- The majority of water on our planet is believed to have come from its interior through outgassing.

[6] *It is now believed that some of the Earth's water may have originated from numerous collisions with small meteors and disintegrating comets when the Earth was very young.*

3. THE VERTICAL STRUCTURE OF THE ATMOSPHERE

A vertical profile of the atmosphere reveals that it can be divided in a series of layers. Each layer may be defined in a number of ways: by the manner the air temperature varies through it, by the gases that comprise it, or even by its electrical properties. At any rate, before we examine these various atmospheric layers, we need to look at the vertical profile of 2 important variables: air pressure and air density.

3.1. A brief look at air pressure and air density

Air molecules (as well as everything else) are held near the surface by *gravity*. This strong invisible force pulling down on the air above squeezes (compresses) air molecules closer together, which causes their number in a given volume to increase. The more air above a level, the greater the squeezing effect, or compression.

Gravity also has an effect on the weight of objects, including air. In fact, *weight* is the force upon an object due to gravity. Weight is defined as the mass of an object time the acceleration of gravity:

Weight = mass x gravity

An object mass is the quantity of matter in the object. Consequently, the mass of air in a rigid container is the same everywhere in the universe. However, the weight of this container on the Moon would only be one sixth of the one on Earth.

The **density** of air (or any substance) is determined by the masses of atoms and molecules and the amount of space between them. In other words, density tells us how much matter is in a given space (that is, volume):

Density = mass / volume

When mass is given in grams (g) or kilograms (kg), volume is given in cubic centimetres (cm^3) or cubic metres (m^3). Near seal level, air density is about 1.2 kilogram per cubic metre (nearly 1.2 ounces per cubic foot).

Because there are appreciably more molecules within the same volume near the Earth's surface than at higher levels, air density is greatest at the surface and decreases as we move up into the atmosphere.

Notice, on the following figure, that, because air is compressed, air density decreases rapidly at first, then more slowly as we move farther away from the surface.

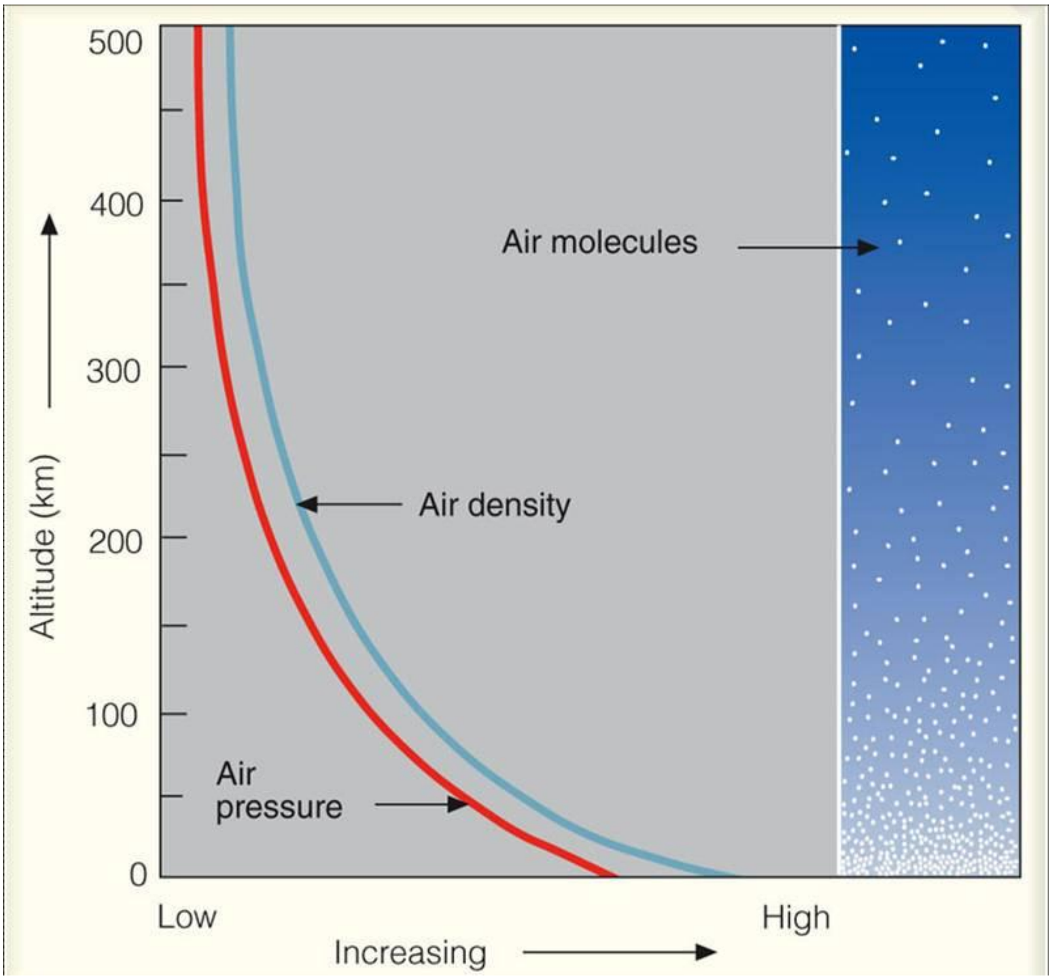

Figure 5: Air pressure and density variation with altitude

Air molecules are in constant motion. On a mild spring day near the surface, an air molecule will collide about 10 billion times each second with other air molecules. It will also bump against other objects around it (houses, trees, flowers, grounds and people). Each time an air molecule bounce against an object, it gives a tiny push. This small pushing force exerted over the area of contact is what defines the **pressure**:

Pressure = force / area

If we weigh a column of air 1 cm^2 in cross section, extending from the average height of the ocean surface (sea level) to the 'top' of the atmosphere, it would weigh nearly 1 kg.
If more molecules are into the column, it becomes denser. Air weighs more and the surface pressure goes up and vice versa. So the **air pressure** can be changed by changing the mass above the surface.

The most common unit found on surface maps is the *millibar*[7] (mb), although the hectopascal (hPa) is gradually replacing the millibar as the preferred unit of pressure on surface charts.

[7] *By definition, a bar is a force of 100,000 newtons (N) acting on a surface area of 1 square metre (m^2). A newton is the amount of force required to move an object with a mass of 1 kilogram (1 kg) so that it increases its speed at a rate of 1 metre per second (m/s) each second. Because the bar is a relatively large unit and because surface pressure are usually small, the unit of pressure most commonly found on surface maps is the millibar (mb), where 1 bar = 1000 mb. The unit of pressure designed by the International System (SI) of measurements is the pascal (Pa), where 1 pascal is a force of 1 newton acting on a surface of 1 square metre. A more common unit is the hectopascal (hPa), as 1 hectopascal equals 1 millibar.*

At sea level, the average, or standard, value for atmospheric pressure is:

1013.25 mb = 1013.25 hPa

Billions of air molecules push constantly on the human body and this force is exerted equally in all directions. We are crushed by it because billions of molecules inside our body push outward just as hard. Air molecules not only take up space (freely darting, twisting, spinning and colliding with everything around them), they also have a weight. In fact, air is surprisingly heavy. The weight of all the air around the Earth is a staggering 5600 trillion tons!

The pressure at any level in the atmosphere may be measured in terms of the total mass of air above any point. As we climb in elevation, fewer ait molecules are above us. Therefore, *atmospheric pressure always decreases with increasing height*. Like air density, air pressure decreases rapidly at first, then more slowly at higher levels.

The following figure illustrates how rapidly air pressure decreases with height:

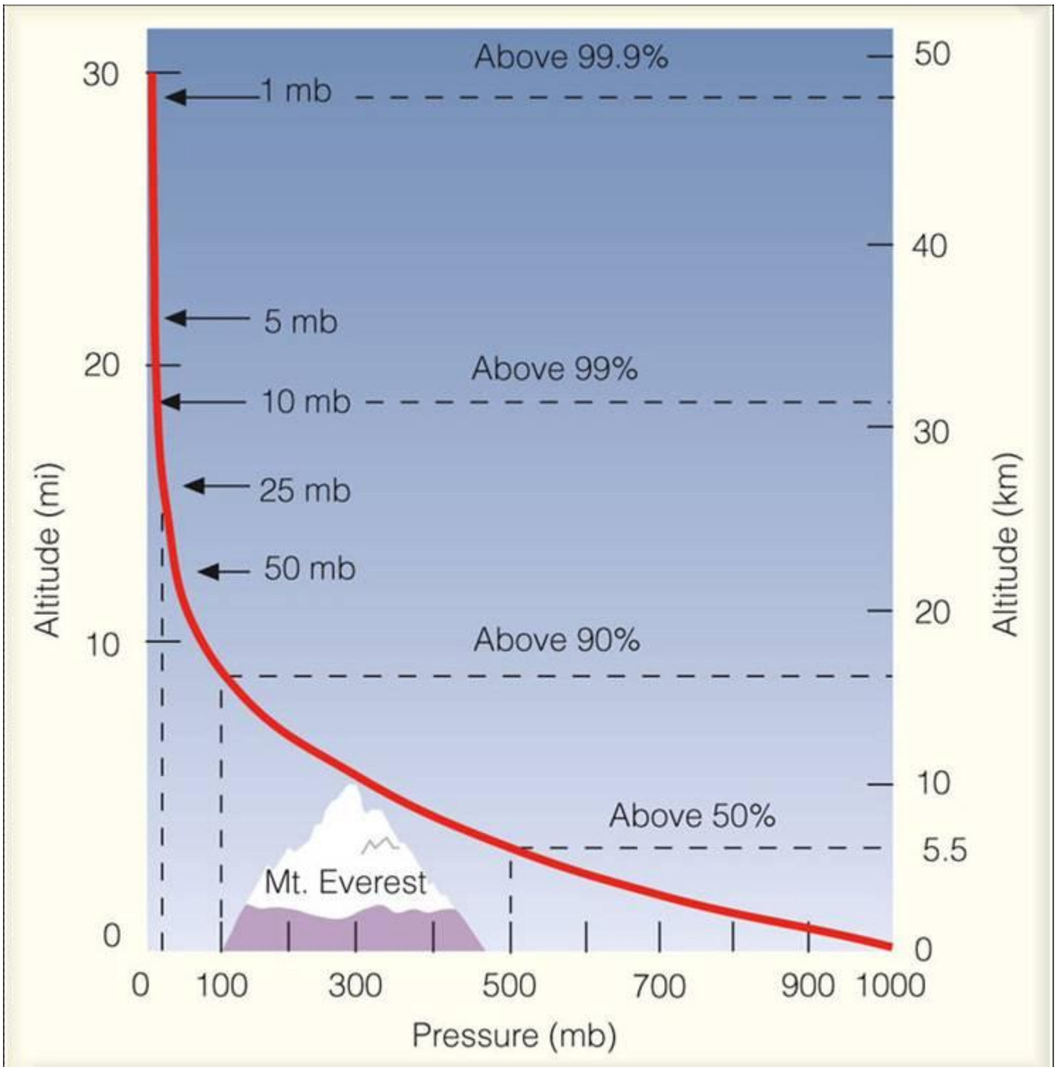

Figure 6: Exponential decrease of air pressure with altitude

Near sea level, atmospheric pressure is usually close to 1000 mb. Normally, just above sea level, atmospheric pressure decreases by about 10 mb for every 100 metres increase in elevation. At higher levels, air pressure decreases much more slowly with height. With a sea level pressure near 1000 mb, we can see that, at an altitude of about 5.5 km, the air pressure is about 500 mb, or one half of sea level pressure, meaning that at a mere 18,000 ft above the surface, we are above one half of all the molecules in the atmosphere.

At an elevation approaching the summit of Mount Everest (about 9 km or 29,000 ft), the air pressure would be about 300 mb. The summit is above nearly 70% of all the molecules in the atmosphere. At an altitude of about 50 km, the air pressure is about 1 mb, which means that 99.9% of the molecules are below this level. Yet, the atmosphere extends upwards for many hundreds of kilometres, gradually becoming thinner and thinner until it ultimately merges with outer space.

3.2. Layers of the atmosphere

We've just seen that both air density and air pressure decrease with height above the Earth, rapidly at first, then more slowly. *Air temperature*, however, has a more complicated vertical profile[8].

Look closely at the following figure and notice that air temperature normally decreases from the Earth's surface up to an altitude of about 11 km (nearly 36,000 ft or 7 miles).

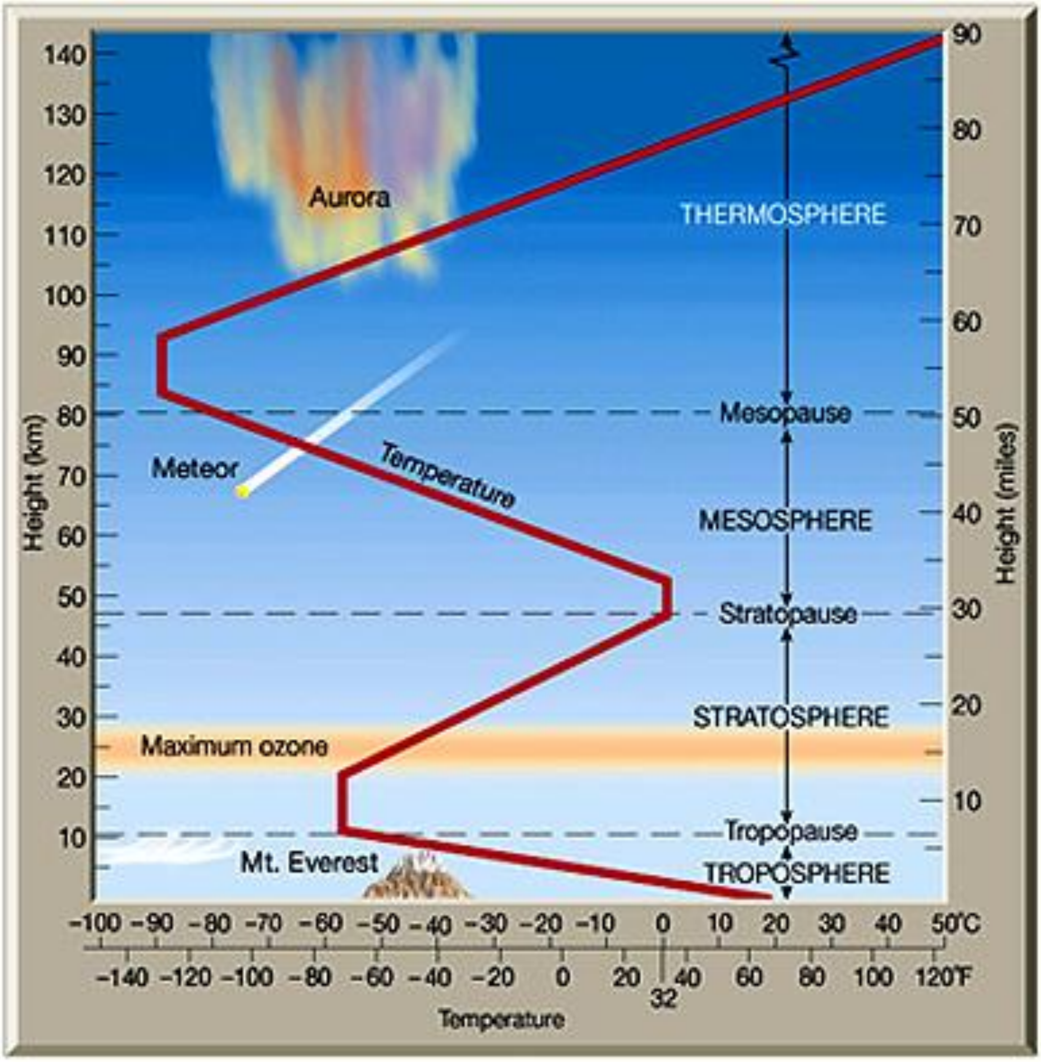

Figure 7: Vertical profile of temperature with altitude and atmospheric layers

This decrease in temperature with increasing height is due primarily to the fact that sunlight warms the Earth's surface, and the surface, in turn, warms the air above it.

[8] *Air temperature is the degree of hotness or coldness of the air and it is also a measure of the average speed of the air molecules.*

3.2.1. Temperature lapse rate

The rate at which the air temperature decreases with height is called temperature **lapse rate**. The *average* (or *standard*) *lapse rate* in this region of the lower atmosphere is about 6.5°C for every 1000 m rise in elevation (or about 3.6°F per 1000 ft).

On some days, the air temperature would become colder more quickly with height, this would steepen (increase) the lapse rate. On other days, the air temperature would decrease colder more slowly with height and the lapse rate would be less. Occasionally, the air temperature may actually *increase* with height, producing a condition known as **temperature inversion**.

So, the lapse rate fluctuates, varying from day to day and season to season. Lapse rate values affect atmosphere stability and are therefore closely linked to thunderstorms as we will see in the appropriate chapter.

3.2.2. Troposphere

The region of the atmosphere from the surface up to about 11 km contains all the weather we are familiar with on Earth. Also, this region is kept well stirred by rising and descending air currents. Here, it is common for air molecules to circulate through a depth of more than 10 km in just a few days. This region of circulating air extending upwards from the Earth's surface to where the air stops becoming colder with height so called the **troposphere** (from the Greek *tropein*, meaning to turn or change).

The instrument used to measure the vertical profile of air temperature in the atmosphere up to an elevation sometimes exceeding 30 km (100,000 ft) is the **radiosonde**. It is a small lightweight box equipped with weather instruments and radio transmitter. It is attached to a chord that has a parachute and a helium filled balloon. As the balloon rises, the radiosonde measures air temperature (through a thermistor), humidity (by sending a current through a carbon-coated plate) and pressure (via a small barometer). All of this information is transmitted to the surface by radio. Special tracking equipment at the surface may also be used to provide a vertical wind profile (when winds are added, we talk about a *rawinsonde*). When plotted on a graph, the vertical distribution of temperature, humidity and wind is called a sounding. Eventually, the balloon bursts and the radiosonde returns to Earth, slowed down by it parachute.

3.2.3. Stratosphere and tropopause

Notice, in the previous figure, that just above 11 km the air temperature stops decreasing with height. Here the lapse rate is zero. This region, where the air temperature remains constant with height, is referred to as an *isothermal* zone. The bottom of this zone marks the top of the troposphere and the beginning of another layer, the **stratosphere**.

The boundary separating the troposphere from the stratosphere is called the **tropopause**. Its height varies. It is normally found at higher elevations over equatorial regions (16 km average height) and decreases in elevation as we travel poleward (8 km average height at the Poles). Generally, the tropopause is higher in the summer and lower in the winter at all latitudes. The lower the tropopause, the warmer it is: it would be -50°C at the Poles when it is -80°C at the Equator at the same season. It is the opposite of surface temperatures and it may sound bizarre but it is down to the fact that cold air is much denser, therefore the thickness of the layer of air in less. More will be explained in other chapters about this.

In some regions, the tropopause 'breaks' and is difficult to locate and, here, scientists have observed mixing of tropospheric and stratospheric air. These breaks also mark the position of the *jet streams* (high winds that meander in a narrow channel, often at speeds exceeding 100 knots[9]).

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[9] A knot is a nautical mile per hour. 1 knot is equal to 1.15 miles per hour or 1.85 kilometre per hour.

From the previous figure, we can see that, in the stratosphere at an altitude near 20 km (12 miles), the air temperature begins to increase with height, producing a *temperature inversion*. The inversion region, along with the lower isothermal layer, tends to keep the vertical currents of the troposphere from spreading into the stratosphere. The inversion also tends to reduce the amount of vertical motion in the stratosphere itself. It is a stable, stratified layer.

Even though the air temperature is increasing with height, the air at an altitude of 30 km is extremely cold, averaging less than -46°C. At this level, above polar latitudes, the air temperatures can change dramatically from one week to the next, as *sudden warming* can raise the temperature in one week by more than 50°C.

The reason for the inversion in the stratosphere is that the ozone plays a major plays in heating the air at this altitude. The following figure explains the 2 step process in ozone creation. The second step releases energy in the form of heat.

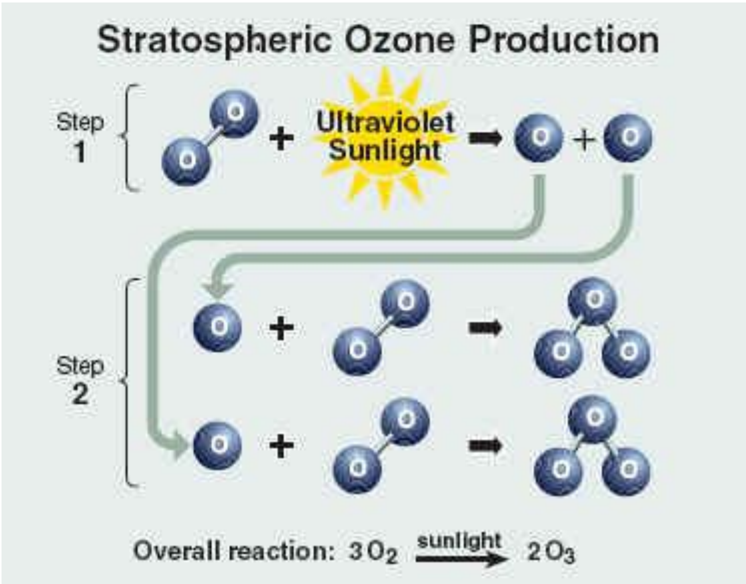

Figure 8: 2 step chemical reaction for ozone creation

Ozone molecules are very efficient at absorbing ultraviolet (UV) light from the Sun. Some of this absorbed energy warms the stratosphere, explaining the inversion.

Notice that the level of maximum ozone concentration is observed near 25 km (at mid-latitudes), yet the stratospheric air temperature reaches a maximum near 50 km. The reason for this phenomenon is that the air at 5- km is less dense than the air at 25 km, and so the absorption of intense solar energy at 50 km raises the temperature of fewer molecules to a much greater degree. Moreover, much of the solar energy responsible for the heating is absorbed in the upper part f the atmosphere and therefore doesn't reach down to the level of maximum ozone. And due to the low air density, the transfer of energy downward from the upper stratosphere is quite poor.

3.2.4. Mesosphere and stratopause

The next layer up from the stratosphere is the **mesosphere** (middle sphere). The boundary near 50 km, which separates these layers, is the *stratopause*. The air at this level is extremely thin and the atmospheric pressure is quite low, averaging about 1 mb, meaning that 99.9% of the atmosphere mass is located below this level.

If unprotected and exposed to conditions at this altitude, apart from almost immediate suffocation due to the far fewer oxygen molecules, other effects would be severe burns from high energy UV rays and body fluids would start to boil due to the very low pressure.

The air temperature in the mesosphere decreases with height, a phenomenon due, in part, to the fact that there is little ozone in the air to absorb solar radiation. Consequently, the molecules (especially those near the top of the mesosphere), lose more energy than they are able to absorb, which results in an energy deficit a cooling. So we find the air in the mesosphere becoming colder with height up to an elevation near 85 km. At this altitude, the temperature of the atmosphere reaches its lowest average value -90°C.

3.2.5. Thermosphere and mesopause

The 'hot layer' above the mesosphere is the **thermosphere**. The boundary that separates the lower, colder mesosphere from the warmer thermosphere is the *mesopause*. In the mesosphere, oxygen molecules absorb energetic solar rays, warming the air. Because there are relatively few atoms and molecules in the thermosphere, the absorption of a small amount of energetic solar energy can cause a large increase in air temperature. Furthermore, because the amount of solar energy affecting this region depends strongly activity, temperatures in the thermosphere vary from day to day. Differences between quiet Sun and active Sun can account for 1000°C temperature difference. The low density of the thermosphere also means that an air molecule will move an average distance (called *mean free path*) of over 1 km before colliding with other air molecules. At the Earth's surface, the mean free path is in the order of a millionth of a centimetre.

Because the air density in the upper thermosphere is so low, air temperatures cannot be measured directly. They can, however, be determined by observing the orbital change of satellites caused by the drag of the atmosphere. Even though air is extremely tenuous, enough air molecules strike a satellite to slow it down, making it drop into a slightly lower orbit. For this reason, *Sky Lab* fell to Earth in July 1979 and the spacecraft *Solar Max* fell in December 1989). The amount of drag is related to air density which itself is related to temperature. Therefore, by determining air density, scientists are able to construct a vertical profile of air temperature.

At the top of the thermosphere, about 500 km (300 miles) above the Earth's surface, molecules can move distances of 10 km before colliding with other molecules. Here the lighter, faster-moving molecules travelling in the right direction can actually escape the Earth's gravitational pull.

3.2.6. Exosphere, homosphere and heterosphere

The region where atoms and molecules shoot off into space is sometimes referred to as the exosphere, which represents the upper limit of our atmosphere.

If we were to divide the atmosphere into layers based on their composition, as opposed to their temperature profiles, we'd find that the composition remains fairly uniform (78% of nitrogen, 21% of oxygen) below the thermosphere owing to turbulent mixing. This lower, well-mixed region is known as the **homosphere**. In the thermosphere, collision between atoms and molecules are infrequent and the air is unable to keep itself stirred. As a result diffusion (mass transport without requiring bulk motion) takes over as heavier atoms and molecules (such as oxygen and nitrogen) tend to settle at the bottom of the layer, while lighter gases (such as hydrogen and helium) float to the top. The region from about the base of the thermosphere to the top of the atmosphere is often called the **heterosphere**.

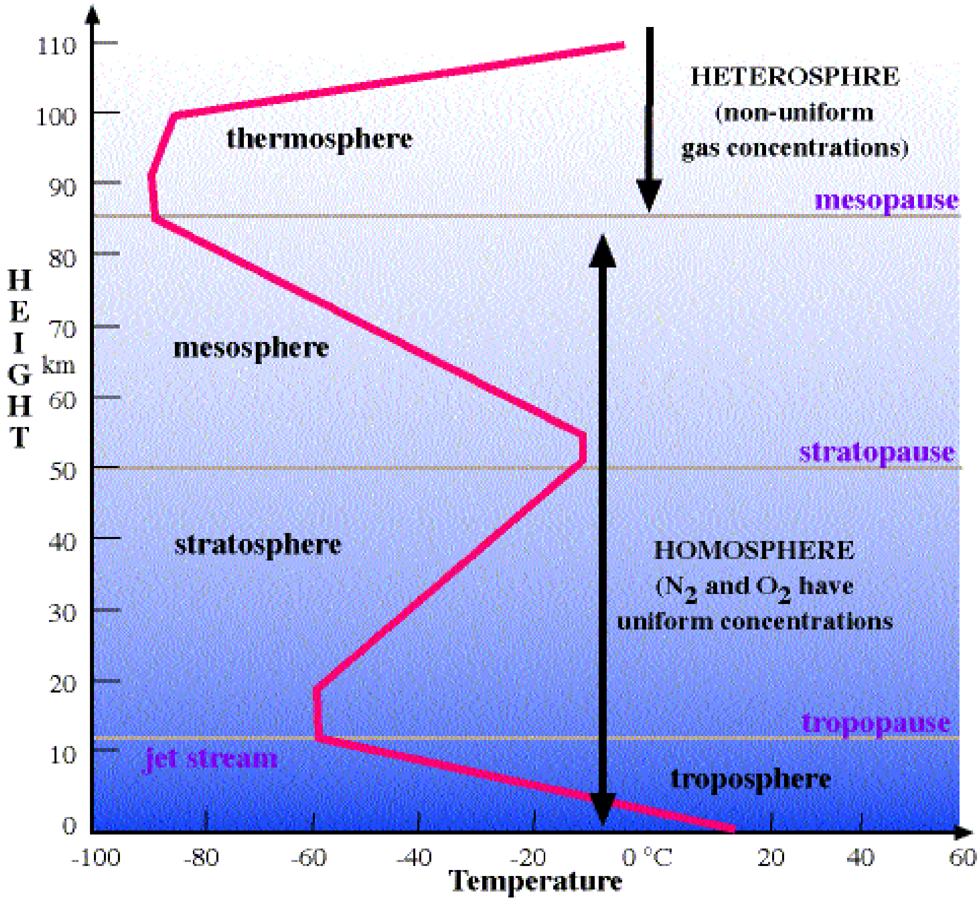

Figure 9: Homosphere and heterosphere in relation to atmospheric layers

3.2.7. Ionosphere

The **ionosphere** is not really a layer, but rather an electrified region in the upper atmosphere where fairly large concentrations of ions and free electrons exist. Ions are atoms that have lost (or gained) one or more electrons through interactions with energetic particles.

The lower region of the ionosphere is usually about 60 km above the Earth's surface. From this level, the ionosphere extends upwards to the top of the atmosphere. Hence the bulk of the ionosphere is in the thermosphere.

The ionosphere plays a major role in radio communications. The lower part, called the D layer, reflects standard AM radio waves back to Earth, but at the same time, it seriously weakens them through absorption. At night, though, the D layer gradually disappears and AM waves are able to penetrate higher into the ionosphere (into the E and F layers), where the waves are reflected back to Earth. Because there is, at night, little absorption of radio waves in the higher reaches of the ionosphere, such waves bounce repeatedly from the ionosphere to the

Earth's surface and back to the ionosphere again. In this way, standard AM radio waves are able to travel hundreds of kilometres at night.

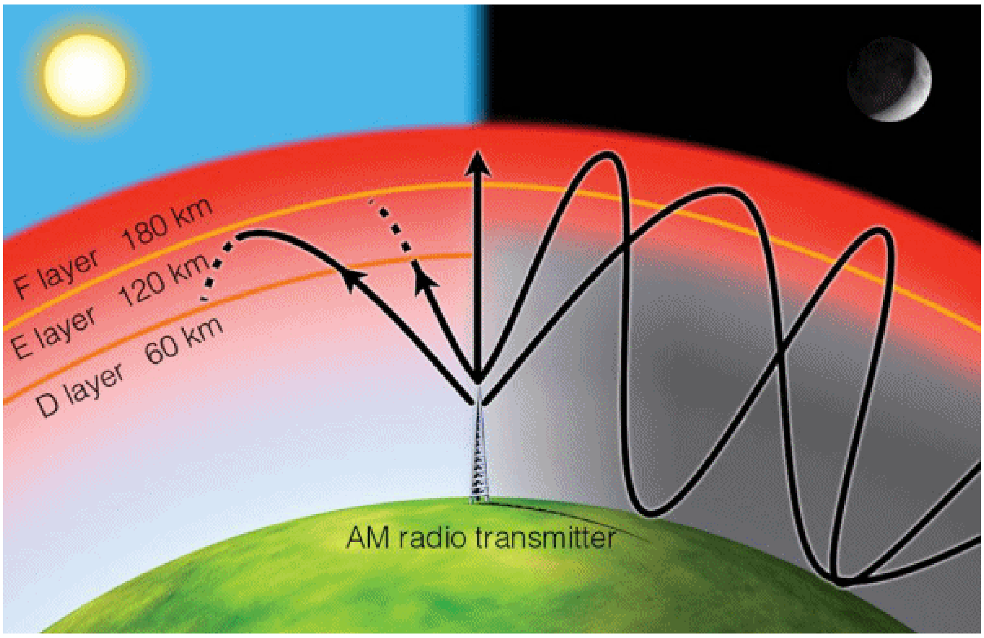

Figure 10: Ionosphere layers and AM radio wave propagation

Around sunrise and sunset, AM radio stations usually make 'necessary adjustments' to compensate for the changing electrical characteristics of the D layer. Because they can broadcast over a greater distance at night, most AM stations reduce their outputs near sunset. This reduction prevents 2 stations, both transmitting on the same frequencies but hundreds of kilometres apart, from interfering with each other's radio programs. At sunrise, as the D layer intensifies, the power supplied to AM radio transmitters is normally increased. FM stations do not need to make these adjustments because FW radio waves are shorter than AM waves and are able to penetrate through the ionosphere without being reflected.

BRIEF REVIEW 2

- Atmospheric pressure at any levels represents the total mass of air above that level and atmospheric pressure **ALWAYS** decreases with increasing height above the surface.
- The atmosphere may be divided into layers according to its vertical temperature profile, its gaseous composition or its electrical properties.
- Zone at the Earth's surface is the main ingredient of photochemical smog, while ozone in the stratosphere protects life on Earth from the Sun's harmful ultraviolet rays.

We will now turn our attention to weather events that take place in the lower atmosphere. As you read the remainder of this chapter, keep in mind that the content serves as a broad overview of material to come in later chapters, and many of the concepts and ideas you encounter are designed to familiarize you with items of everyday **meteorology**.

4. WEATHER AND CLIMATE

When we talk about the **weather**, we are talking about the condition of the atmosphere at any particular time and place. Weather is comprised of the following elements:

- *Air temperature: the degree of hotness or coldness of the air*
- *Air pressure: equivalent to the force of the air over an area*
- *Humidity: a measure of the amount of water in the air*
- *Clouds: a visible mass of tiny water droplets and/or ice crystals that are above the Earth's surface*
- *Precipitation: any form of water, either liquid or solid (rain or snow), that falls from the clouds and reaches the Earth's surface*
- *Visibility: the greatest distance on can see*
- *Wind: the horizontal movement of air*

If we measure and observe these **weather elements** over a specified interval of time, say for many years, we would obtain the 'average weather' or **climate** of a particular region. Climate, therefore, represents the accumulation of daily and seasonal weather events over a long period of time. The concept of climate also includes the extremes of weather (the heat waves of summer and the cold spells of winter) that occur at a particular region.

Over many thousands of years, even the climate changes. Imagine we could photograph the Earth once every thousand years for many hundreds of millions of years. In time-lapse film sequence, these photos would show that not only is the climate altering, but the whole Earth itself is changing as well: mountains would rise up, only to be torn down by erosion; and the entire surface of the Earth would undergo a gradual transformation as some ocean basins widen and other shrink[10].

In summary, the Earth and its atmosphere are dynamic systems that are constantly changing.

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[10] *The movement of the ocean floor and continents is explained in the widely acclaimed theory of plate tectonics, formerly called theory of continental drift.*

4.1. A look at a satellite picture

A good view of the weather can be seen from a weather satellite. The following figure is a satellite photograph of Europe, North Africa and part of the Atlantic Ocean up to Iceland.

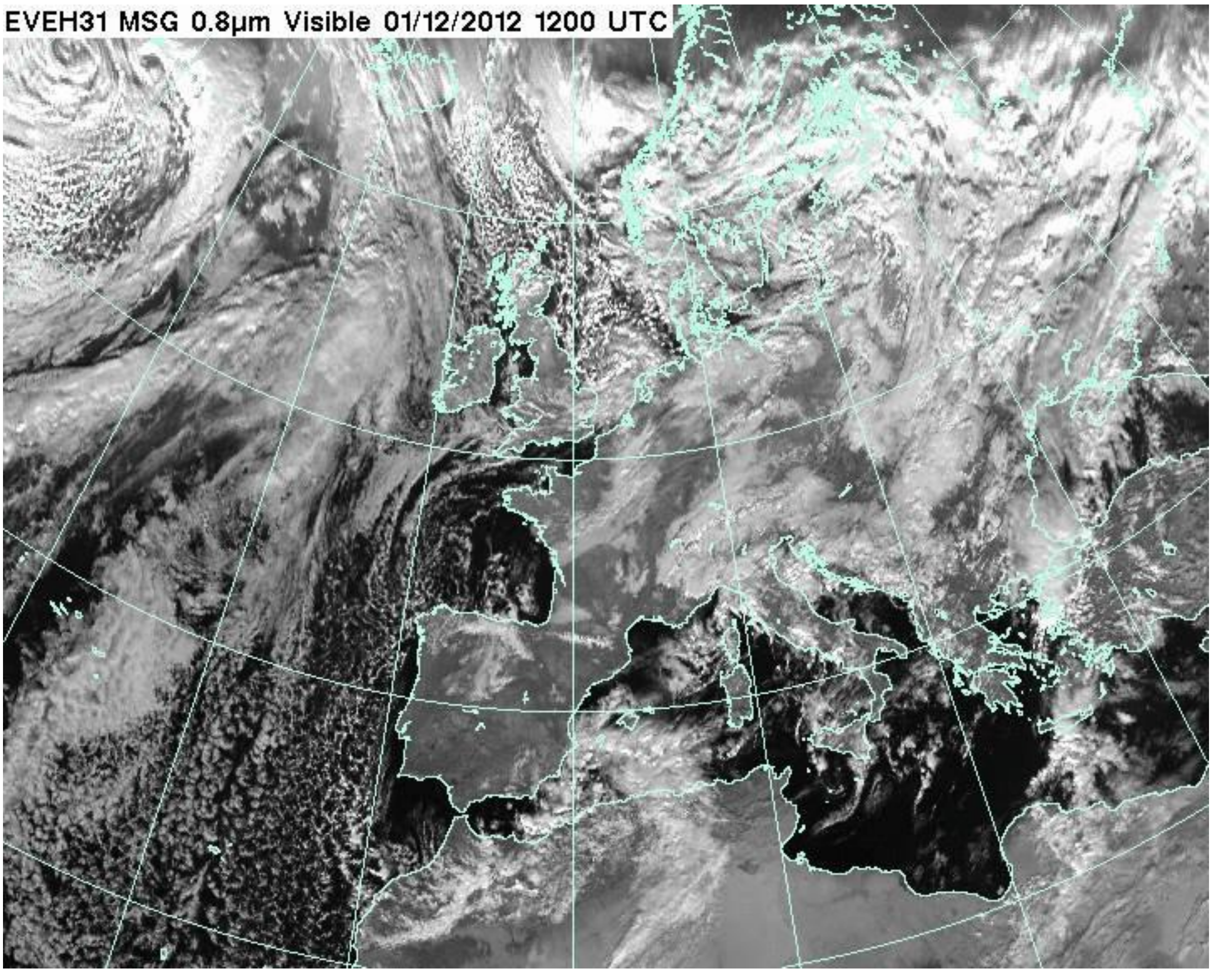

Figure 11: Visible satellite image

The picture was obtained from a geostationary satellite orbiting at about 36,000 km (22,300 miles) above the surface. At this elevation, the satellite travels at the same rate as the Earth spins, which allows it to remain positioned above the same spot and continuously monitor what is taking place below it.

The angled lines running up and down are called *meridians*. The prime meridian, located in Greenwich, serves as a reference for longitude (how far east or west in degrees one is located with regards to the prime meridian).

The arcs parallel to the Equator are called *parallels of latitude*. The latitude of any place is how far north or south, in degrees, it is from the Equator. The latitude of the Equator is 0°, whereas the latitude of the North Pole is 90°N and that of the South Pole is 90°S. The United Kingdom lies is the **middle latitudes**, a region situated between 20°N (or 20°S) and 70°N (or 70°S).

The visible images record visible light from the Sun reflected back to the satellite by cloud tops, land and sea surfaces. They are equivalent to a black and white photograph from space. However, visible pictures can only be made during daylight hours.

4.2. A look at a weather map

Let's consider the following figure showing a surface pressure map for the same period as the satellite picture above.

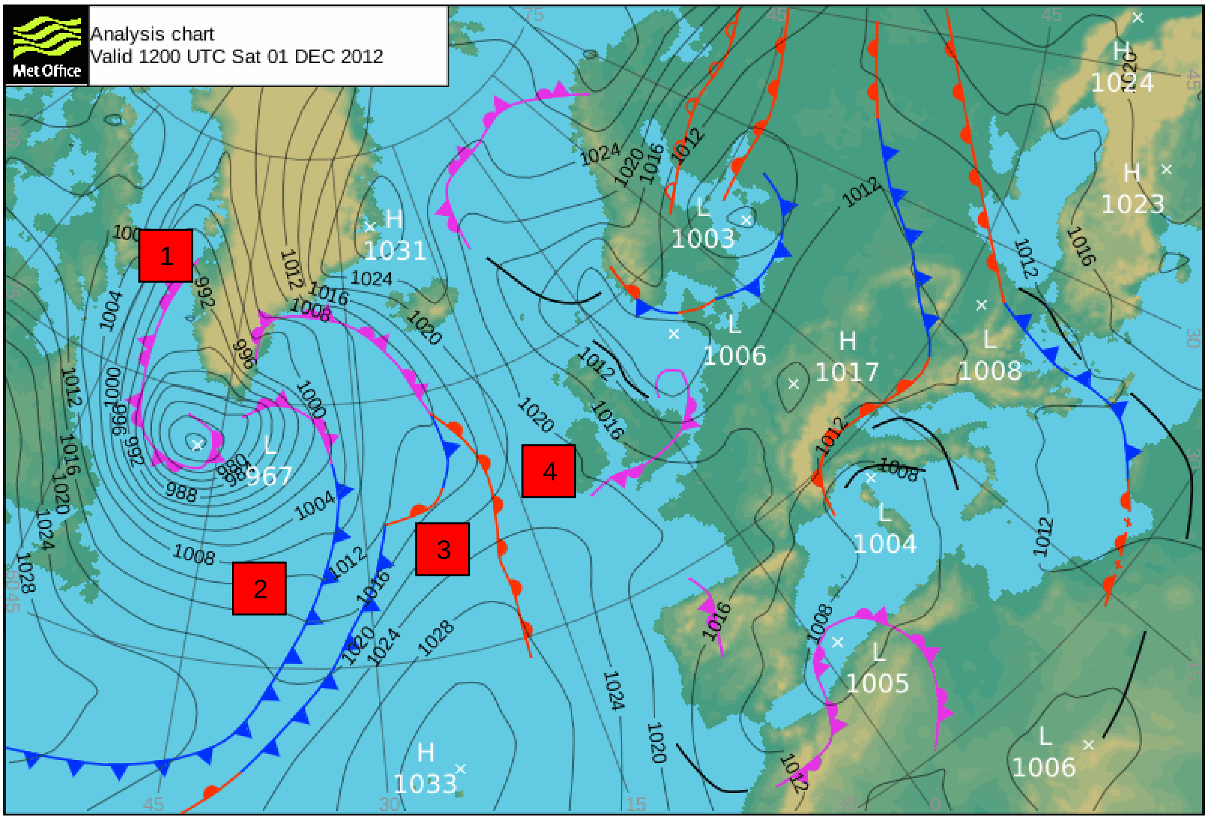

Figure 12: Surface pressure map

The weight of the air above different regions varies, hence, so does the atmospheric pressure.

In the above figure, the letter L indicates a region of low atmospheric pressure, a *low*, which marks the centre of a middle latitude storm. We can see a very deep low pressure system south of Greenland.

The letter H represents regions of high pressure systems, called *highs* or *anticyclones*. A well marked high is located west of Spain, it is the semi-permanent Azores High.

Wind is defined as horizontal movement of air. By convention, the **wind direction** is the direction *from which* the wind is blowing[11]. Winds blow around the highs and lows. The horizontal pressure differences create a force that starts the air moving from higher pressure to lower pressure. Because of the Earth's rotation, the winds are deflected towards the right in the Northern Hemisphere[12]. This deflection causes the winds to blow *clockwise* and *outward* from the centre of highs, and *counter clockwise* and *inward* towards the centre of lows. Outward and inward flow is due to surface friction.

As the surface air spins into the low, it flows together and rises. The rising air cools and the moisture in the air condenses into clouds

As surface air flows outwards from the centre of the high, air sinking from above must replace the laterally spreading air. Since sinking air does not usually produce clouds, we generally find clear skies and fair weather associated with areas of high pressure.

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[11] *For example, if you are facing north and the wind is blowing in your face, the wind is a northerly wind.*
[12] *This deflecting force, known as Coriolis force, will be discussed more completely in the chapter on winds.*

The swirling air around the areas of high and low pressures is the major weather producers for the middle latitudes.

Let's have a quick look at the surface pressure chart:

Northerly winds draw very cold air from the arctic regions in area 1. The same goes for area 4.

In area 2, winds are westerly, less cold than in area 1 after their travel over warm seas, but still quite cool.

In area 3, south westerly winds advect (transport horizontally) warm air from the tropical Atlantic.
The (double) cold **front**, drawn in blue with triangles (showing its direction of movement) demarks a region where warm air in area 3 is getting replaced by colder air from area 2

The warm front, drawn in red with filled semi-circles (showing its direction of movement) demarks a region where cold air in area 4 is getting replaced by warmer air from area 3.

Following the fronts north from area 3, we find an occluded front, drawn in pink with alternating triangles and filled semi-circles (showing its direction of movement). It is an area where the faster moving cold air has caught up with the warmer air, undercutting the warm air and forcing it aloft.

Along each of the fronts, warm air is rising, producing clouds and precipitation.

Observing storm systems, one can see that not only do they move, but they constantly change. Steered but the upper level westerly winds, mid-latitudes storm west of area 3 will intensify into a larger storm moving eastward, carrying its clouds and weather with it, given the right upper level conditions.

4.3. Weather and climate in our lives

Weather and climate play a major role in our lives. They affect us in many ways but their most immediate effect is on our comfort. Even when we are dressed for the weather properly, wind, humidity and precipitation can change our perception of how cold or warm it feels. On a cold windy day, the effects of *wind chill* tell us that it feels much colder than it really is, and if not properly dressed, we run the risk of *frostbite* or even *hypothermia*[13]. On a hot humid day, we normally feel uncomfortable. If we become too hot, our body overheats and *heat exhaustion* or even *heat stroke* may result.

Weather affects how we feel in other way too. Arthritic pain is most likely to occur when humidity is accompanied by falling pressures.

5. SUMMARY

This chapter provided us with an overview of the Earth's atmosphere. Our atmosphere is a rich in nitrogen and oxygen as well as smaller amounts of other gases, such as water vapour, carbon dioxide and other greenhouse gases whose increasing levels may result in global warming. We examined the early atmosphere and found it to be much different than the air we breathe today.

We investigated the various layers of the atmosphere and found that stratospheric ozone, which protects us from the Sun's harmful ultraviolet rays, had been decreasing in concentration as gases such as chlorofluorocarbons in the stratosphere break apart and release ozone-destroying chlorine. We found that the coldest part in our atmosphere is the mesosphere, that the warmest is the thermosphere, and that all the weather we have come to know exists in the troposphere. We then looked at the ionosphere, the region in the upper atmosphere that contains large numbers of ions and free atoms.

We looked briefly at a satellite picture and a weather map and we were introduced concepts such as fronts, which are areas where air masses with differing properties (temperature, moisture content) replace each other.

[13] *Rapid, progressive and mental collapse that accompanies the lowering of human body temperature.*