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Air quality management

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1.1

Contents

Section 1: Air basics

1.1 Introduction

Without the layer of air that surrounds our planet, neither we nor any of the other forms of life that have evolved on Earth could exist. The general term for this layer of air is ‘atmosphere’, a word derived from the Greek *atmos* (vapour) and *sphaira* (ball or sphere). Of all the subsystems within the environmental system, the atmosphere has a number of unique characteristics. It is continuous around the Earth (Figure 1), but compared with the size of the Earth, the atmosphere is a thin shell (Figure 2). The part of the atmosphere we know best and live in – the *troposphere* – is an even thinner shell, only around 12 kilometres (7.5 miles) thick.

Figure 1 The Earth and its atmosphere from space

View description

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Figure 2 Space Shuttle photograph of the Earth: the thin atmosphere is lit by the setting Sun

View description

If the Earth were the size of an apple, the atmosphere would have the thickness of the apple peel, yet this thin film of gases fulfils many essential functions. It is in the troposphere that all weather occurs; it is only here that life exists. Wind systems and rainfall patterns result from the differential heating by solar energy of the Earth's surface and, subsequently, the atmosphere. Such weather manifestations are visible from space.

This text introduces the components of the atmosphere, and how meteorological conditions influence air quality. It then goes on to consider the main sources of air pollution. The adverse effects of air pollutants on both human beings and the environment are detailed, together with methods of measuring air pollutants. Methods of preventing or minimising air pollution are then outlined. Finally, air pollution modelling is introduced: this allows prediction of air quality and the impact of air pollutants, and can also be used to determine the effectiveness of any control measures that are implemented.

1.2 Clean air – a basic human need

Have you ever thought about how much air you need to breathe each day? We take the air for granted, but think how long you can go without food or water compared to how long you can hold your breath. The basic biological air requirements for a person weighing around 68 kg are summarised in Table 1.

Table 1 Air requirements for human activity at typical ground-level pressure (100 kPa)

Activity	l min^{-1}	l $hour^{-1}$
Resting	7.4	444
Doing light work	28	1680
Doing heavy work	43	2580

Based on this information, if we take a working day to comprise 7 hours of heavy work, 7 hours of light work and 10 hours of rest, we need 34 260 litres or 34.26 m^3 of air per day. Taking the density of air as 1.29 kg m^{-3}, the mass of air required comes to 44.20 kg. In comparison, we eat no more than about 1.5 kg of food each day, so our air requirement is nearly 30 times our food requirement. Similarly, we probably drink no more than about 2.5 kg of water each day. This indicates why air quality is so important; any contamination needs to be much lower in air than in food and water if we are to ensure that our total intake of potentially harmful substances does not put our health at risk. We cannot choose the air we breathe.

In our modern, technological society, we also need air to burn fuels for heating and for transport. Look at the boiler in Figure 3. To burn 0.8 litres of oil per minute it needs 8.5 m^3 of air per minute. A large boiler in a power station needs considerably more air.

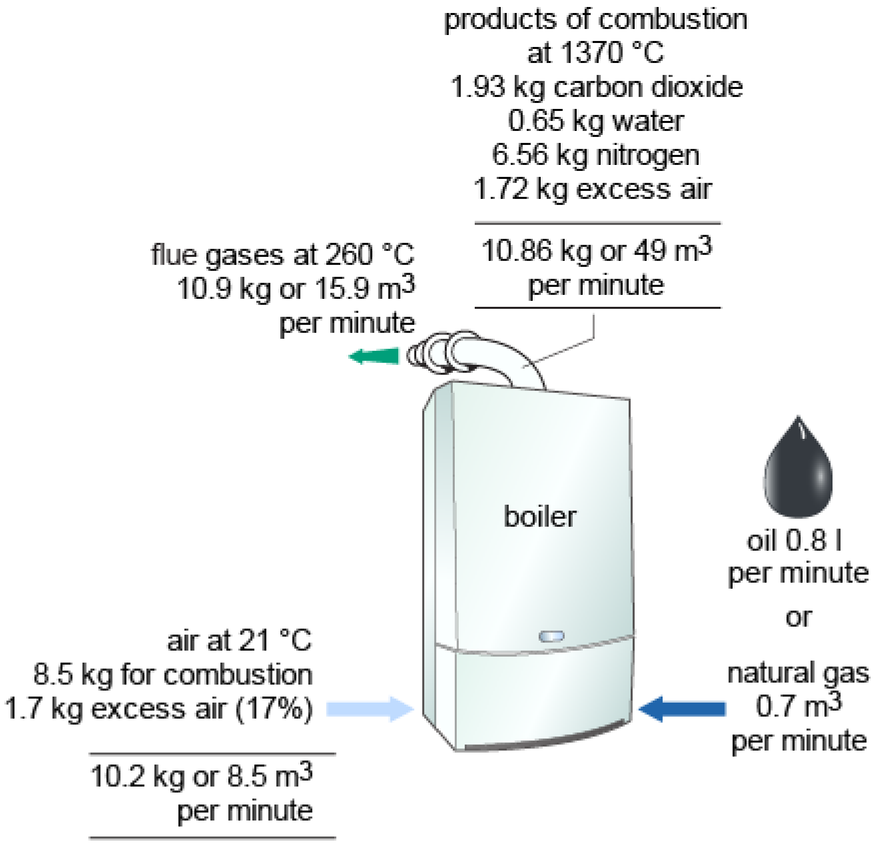

Figure 3 Fuel and air requirements for a typical central heating and hot water boiler

View description

Determination of the stoichiometric (theoretical) air/fuel ratio for the complete combustion of petrol

Modern petrols are blends of hydrocarbons and additives, but we can represent an average formulation in terms of a single component, octane (C_8H_{18}). A balanced chemical equation for the combustion of this fuel is:

$$C_8H_{18} + 12.5\ O_2 \rightarrow 8CO_2 + 9H_2O$$

The mass of one mole of octane is given by:

$$(8 \times 12) + (18 \times 1) = 114\ \text{g}$$

The chemical equation tells us that 12.5 moles of molecular oxygen are required for complete combustion of each mole of octane. The mass of this oxygen is given by:

$$12.5 \times 16 \times 2 = 400 \text{ g}$$

Since the percentage by mass of oxygen in air is approximately 23.15 (you can confirm this for yourself later using the values in Table 2), the mass of air required for complete combustion of one mole of octane is given by:

$$(400/23.15) \times 100 = 1728 \text{ g}$$

So the *stoichiometric* air/fuel ratio is:

$$\text{air/fuel} = 1728/114 = 15.16$$

Therefore, each mass unit of petrol needs just over 15 mass units of air. Think of how many cars are on the roads. If each kilogram of fuel requires 15 kg of air for combustion in the engine, you should be able to work out how much air you need for your car each day. The car exhaust also contaminates the air we breathe. You can see that the air is an indispensable resource, which we contaminate by using it.

SAQ 1

Suggest some ways that we as individuals contribute to air pollution.

View answer

This text will examine some aspects of air quality, look at how the air behaves, and consider how we can minimise our impact on what may be regarded as our most precious resource.

1.3 What is air pollution?

The United Kingdom is where the industrial revolution began, bringing with it a legacy of damage to the natural environment and public health. Resources such as water, coal and minerals were exploited, and by the middle of the nineteenth century the air and water were choked with industrial emissions (Figure 4). Indeed, the image of a prospering industry was of smoking chimneys.

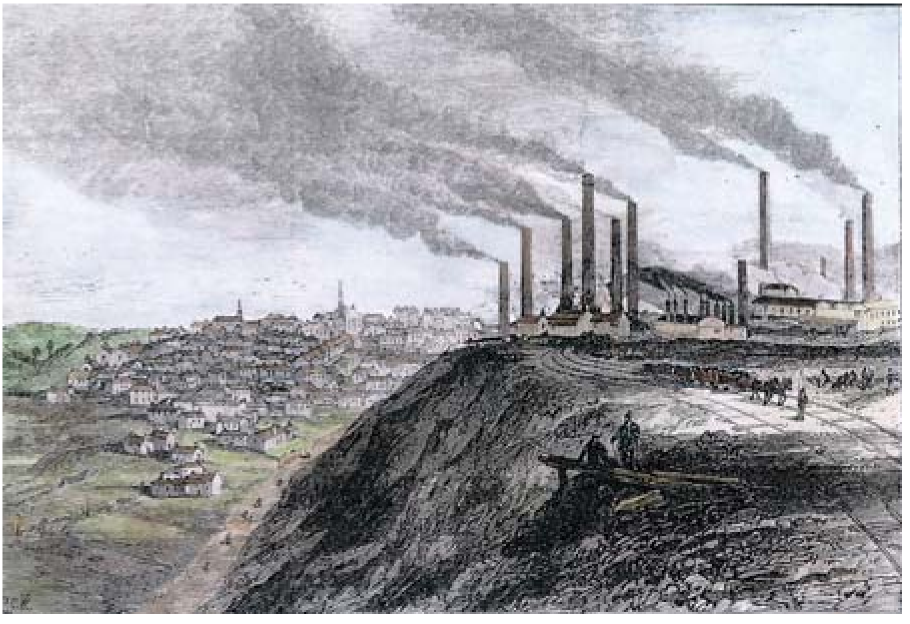

Figure 4 Factory chimneys at Dowlais, South Wales, 1875

View description

The first measures to protect the environment can also be traced back to this period. The air is obviously an important part of the environment to protect – it is essential for the survival of all higher forms of life on the planet. While seemingly vast, the atmosphere accounts for only about 1% of the diameter of the Earth. It is also continuous and so may be contaminated by activities perhaps hundreds or even thousands of miles away. We usually refer to this contamination as air pollution. The World Health Organization (WHO, 2013) has defined air pollution as:

> Contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere.

There are two aspects of air pollution that are of major importance to life on Earth. Some constituents of the atmosphere may have a directly harmful effect on life forms, and other constituents may cause significant damage through changing the Earth's radiative balance. The spatial continuity of the atmosphere makes it nearly impossible to contemplate remediation, so pollutant releases to atmosphere must be considered with caution. Pollutants can be transported great distances, having an impact far from the emission source. A well-known example of this is the catastrophic fire and subsequent explosion at the Chernobyl Nuclear Power Plant in April 1986, in what was then the Soviet Union. This had a widespread effect across much of Europe, with pastures as far away as Wales and the Lake District – around 2300 km from the source – being contaminated due to airborne pollution.

1.4 Air quality

The atmosphere can be subdivided into several layers, but it is the air nearest the ground that is most often of interest to us. The approximate composition of dry air in the lowest part of the atmosphere (the troposphere) is summarised in Table 2.

Table 2 Approximate composition of dry tropospheric air

Gas	Symbol	Typical concentration in air	
		vol. per vol. (ppm[a])	mass per vol. ($\mu g\ m^{-3}$)
Essentially permanent			
Nitrogen	N_2	7.81×10^5	9.76×10^8
Oxygen	O_2	2.095×10^5	2.99×10^8
Argon	Ar	9.34×10^3	1.67×10^7
Neon	Ne	1.836×10^1	1.64×10^4
Helium	He	5.24×10^0	9.40×10^2

Krypton	Kr	1.14×10^{0}	4.263×10^{3}
Xenon	Xe	9×10^{-2}	5.27×10^{2}
Variable			
Hydrogen	H_2	5×10^{-1}	4.5×10^{1}
Methane	CH_4	1.8×10^{0}	1.287×10^{3}
Nitrous oxide	N_2O	3.3×10^{-1}	6.48×10^{2}
Carbon dioxide	CO_2	4.00×10^{2} [b]	7.88×10^{5}
Very variable			
Carbon monoxide	CO	$(5–25) \times 10^{-2}$	
Ozone	O_3 [c]	$(1–5) \times 10^{-2}$	
Nitrogen dioxide	NO_2	$(1–50) \times 10^{-4}$	
Ammonia	NH_3	$(1–100) \times 10^{-4}$	
Sulfur dioxide	SO_2	$(3–3000) \times 10^{-5}$	
Hydrogen sulfide	H_2S	$(<6–600) \times 10^{-6}$	
Carbonyl sulfide[d]	COS	$(4.5–5.5) \times 10^{-4}$	
Water	H_2O	10 ppm to 4%	

[a] ppm = parts per million, i.e. volume of the gas concerned per million volumes of air

[b] Reached in 2013.

[c] Tropospheric ozone can be undetectably low (0 ppbv) or several hundred parts per billion in volume terms (ppbv) in polluted regions. A typical value might be 30 ppbv. Stratospheric ozone varies between 1 and 6 ppmv.

[d] The most abundant sulfur compound naturally present in the atmosphere.

The air around us contains many other compounds not shown in Table 2, but the gases shown are among the most important in any consideration of air quality. In addition, atmospheric *aerosol* is present: a suspension of fine solid or liquid particles (known as *particulate matter* or aerosol particles) in air. It includes substances such as inorganic acids, inorganic salts, a variety of organic compounds, and trace metals. From this you should appreciate that there is no such thing as 'pure air', for air is a mixture.

While the 'permanent' gases are essentially always present at the same concentrations, the composition of the minor (or trace) components is very variable in space and over time. It is the variable components that are often considered air pollutants. All of those shown in the table have natural sources, but are also produced from human activities. When concentrations change to such an extent that local or global air quality deteriorates, we can regard this as air pollution. As you will see later, even the major components (nitrogen and oxygen) take part in chemical reactions in which pollutants may be formed.

There is no space here to review the nature, sources and effects of all air pollutants, and so only a selection will be covered. However, this selection includes several of the more important air pollutants that tend to be the subject of air quality standards in many countries.

SAQ 2

Rank the following permanent atmospheric gases according to their increasing concentrations in the atmosphere. Identify the chemical symbol and give the permanent concentration of each gas.

Gas	Chemical symbol	Concentration	Rank
Nitrogen			
Argon			
Molecular oxygen			

View answer

1.5 The human respiratory system

To conclude this section on air basics, it is worth looking at the behaviour of the human respiratory system in some detail, since the response to gases and particles is somewhat different and there are important implications for the way we measure pollutants. In addition, some of the principles involved in the way the respiratory system handles pollutants are similar to those used by the industrial gas cleaning systems you will meet later.

The lungs (see Figure 5) have evolved to absorb and excrete gases, and are the major route through which toxic substances in the workplace and the ambient atmosphere enter the body. When we inhale, air flows through the nose and mouth, then down the throat to the larynx, where the respiratory system branches off from the oesophagus. From the larynx, the air goes down the trachea, which divides to go to each lung. At the point of division, the air passages are called the bronchi. Each bronchus divides 20–30 times into smaller and smaller branches, becoming the bronchioles that take the air to the different areas of the lung.

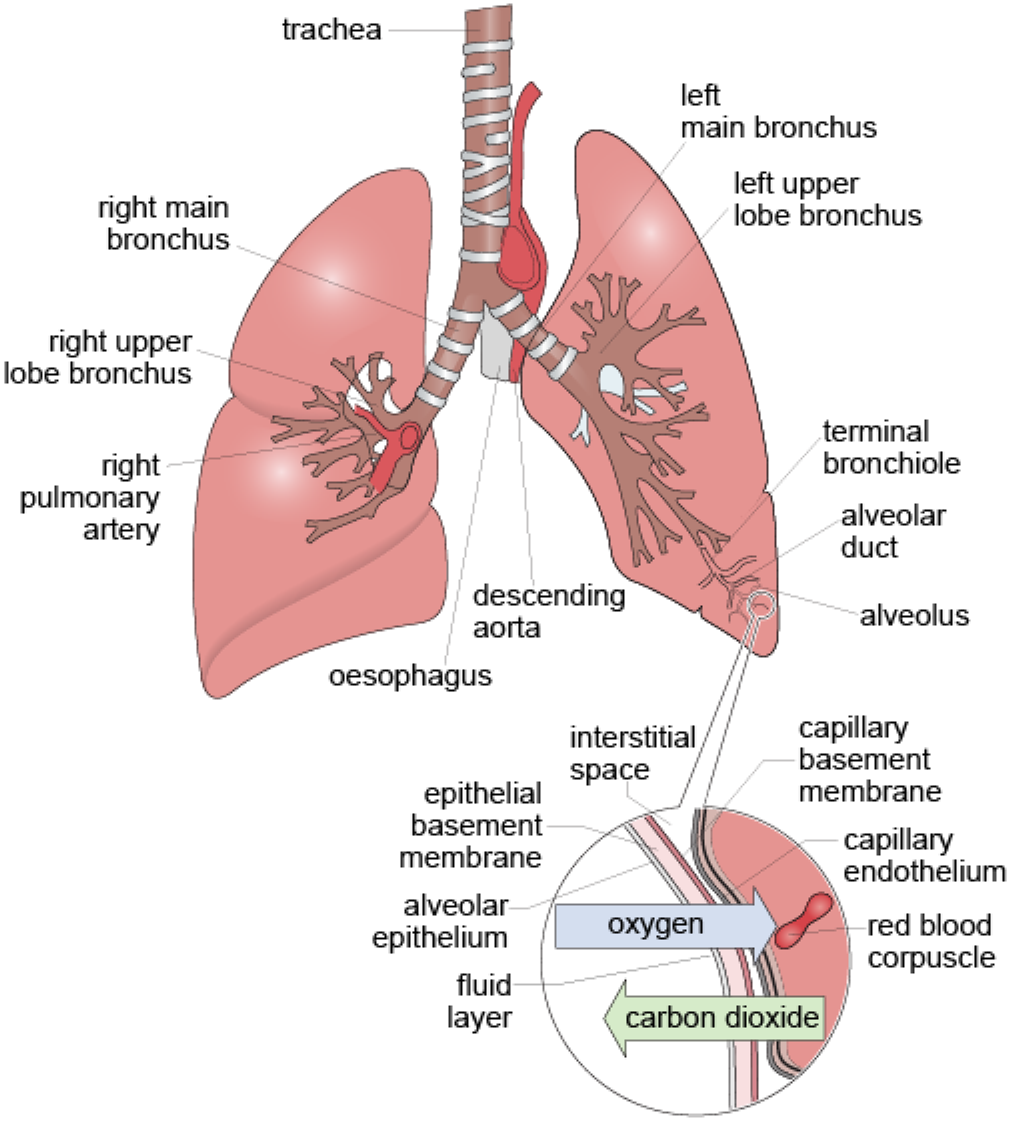

Figure 5 The human lung

View description

Eventually the air reaches a cluster of ‘sacs’ called alveoli, where the actual gas exchange occurs. Adult humans can have up to 300 million alveoli in their lungs. Each of the alveoli has a network of capillaries that carry oxygen-deficient red blood cells very close to the air space in the alveoli. The air in the alveoli is oxygen-rich, so oxygen moves from the alveolar space into the red blood cells by diffusion. This happens very quickly, because the surface area of the alveoli is large and the membrane (pleura) separating each lung from the red blood cells is very thin. (The rate of oxygen diffusion is dependent on surface area, so gas exchange occurs more quickly with larger surface areas – which the many small alveoli provide.)

The lungs are the first organ to be affected by any dusts, metal fumes, solvent vapours and corrosive gases that are not captured by the mucus in the nose, mouth and throat and subsequently expelled.

Particles are removed from a flowing air stream, such as in the respiratory tract, by various physical processes:

- *Interception* – when the trajectory of a particle brings it close enough to graze a surface and become stuck.
- *Impaction* – when the momentum of a particle prevents it from following the change in direction of the air stream (an inertial effect).
- *Sedimentation* – when particles separate out under the action of gravity.
- *Diffusion* – when the random impact of gas molecules causes small particles to move (so-called Brownian motion).

Before reading on, consider in what parts of the human respiratory system each of these processes is likely to occur.

Interception

The nose is our air intake and is lined with hairs, which act as a coarse filter. The nasal mucosa, or damp lining of the nose, also serves as a defence mechanism that deals reasonably well with normal ‘pollution’ levels. However, high levels of dust may overwhelm this primary defence mechanism with two consequences: dust may reach the lower levels of the respiratory system, and the nose will be severely irritated (becoming inflamed and producing a great deal of mucus).

Impaction

Essentially, all particles over 10 μm are removed in the nose at flow rates corresponding to those of moderate exercise. Mouth breathing allows particles up to 15 μm to pass. So, normally, the larger particles in the inspirable fraction of dust are deposited in the nose, pharynx and larynx. Then a second line of defence operates – inertial impaction. The branched respiratory system (see Figure 5) causes some particles over about 4 μm to be thrown to the walls of the system by centrifugal force when the air stream goes round the bends.

Sedimentation and diffusion

Dust particles settling on the epithelium of all but the narrowest pulmonary air vessels are rapidly removed from the lung. The cells lining the bronchi and larger bronchioles are covered with mucus, which traps the dust, and they also have whip-like projections (cilia) on their free surfaces. These cilia move dust particles upwards along the mucociliary escalator towards the trachea (wind pipe), from where they are coughed up or swallowed.

Some of the smaller particles behave more like gas molecules and are small enough to pass through the narrowest pulmonary air vessels (respiratory bronchioles). They may even reach terminal air sacs in the alveolar region of the lung where gas exchange occurs. In these bronchioles and alveoli, there is no mucociliary escalator. Sedimentation is the predominant physical process that removes particles between 0.5 and 1.0 μm in size, while diffusion operates for particles below 0.5 μm – from basic physics, the smaller the particles, the greater the Brownian motion.

However, there is a mechanism for dealing with the small particles. Macrophages are cells that wander through the lung and are able to engulf foreign particles or bacteria. Each macrophage may engulf hundreds of particles. The macrophages are able to pass through alveolar walls, through the walls of larger bronchioles and blood vessels, and through the pleura. If a macrophage carries its dust load through a bronchiole wall then it will reach the escalator and be coughed up, but if it moves through the wall of a blood vessel then it may be carried to another organ. So it is easy to see how inhaled particles can cause damage elsewhere in the body.

Note that particles can only reach the bottom of the lungs (alveoli) if they are small enough – less than 10 μm *aerodynamic diameter*, the so-called PM_{10} fraction (more on this in Section 2). Inhaled particles larger than PM_{10} enter the gut either directly after deposition before entering the lungs or indirectly in mucus from the respiratory system.

SAQ 3

What factors control how particles enter the respiratory system, and what effects should we bear in mind when considering the range of particle sizes?

View answer

1.6 Summary

Air consists of a mixture of gases and is a basic human need. The major components of air are nitrogen and oxygen, with the latter required in respiration and combustion processes. Pollution of the air can have impacts far from the source of pollution. The human respiratory system is able to remove unwanted materials from the air that we breathe, through the processes of interception, impaction, sedimentation and diffusion.

Section 2: Meteorology and air pollutants

2.1 Introduction

You may have noticed that sometimes weather forecasts comment on air quality, with reference to sulfur dioxide or nitrogen oxides in the winter, and ozone in the summer. You may conclude from this that air quality and meteorology (the science of the atmosphere) are connected, and this section will examine some of the links. Before reaching that point, however, you need to understand the nature of the atmosphere and the processes that occur in it.

The atmosphere of the Earth or any other planet is often considered in terms of its vertical temperature profile. The profile of the Earth's atmosphere reveals five regions, the innermost four of which are illustrated in Figure 6 (note that the aspect ratio of the figure has been stretched enormously in the vertical – remember, from Section 1, the thinness of the atmosphere relative to the Earth's diameter). This figure is linear in altitude, and so makes the troposphere appear to be a minor part of the atmosphere; however, if we were to consider pressure or mass of atmosphere, we would find that approximately 90% of the atmosphere's mass resides in the troposphere.

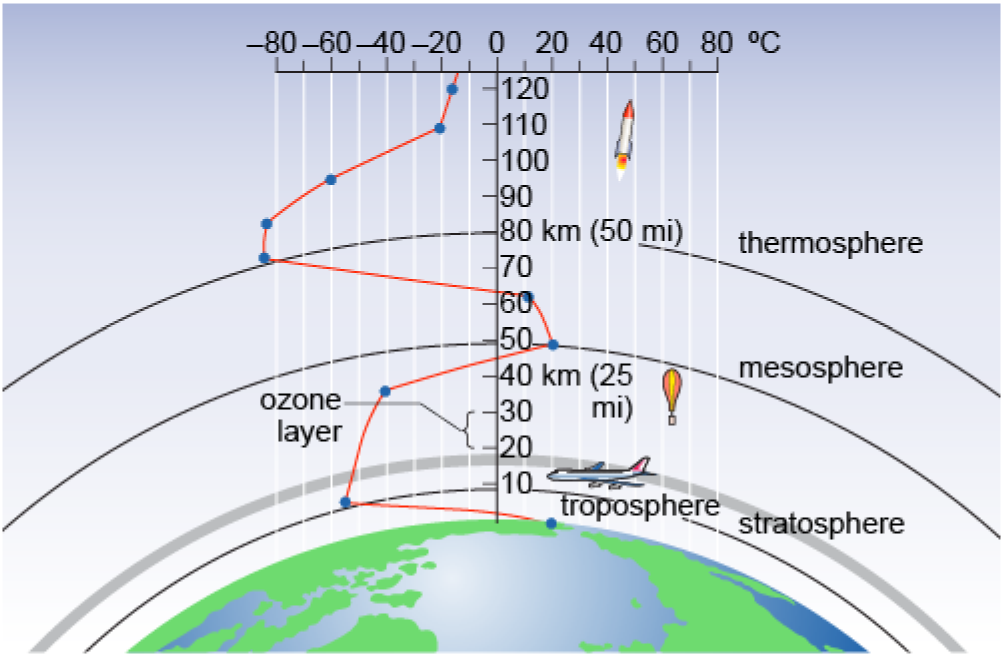

Figure 6 The structure of the atmosphere and its temperature profile (shown in red)

View description

Lower layers

The lowest region is the *troposphere*, in which we live and where normal weather processes dominate. As such, it is of immediate interest to us as residents of the land. The thickness of the troposphere varies from about 17 km at the equator to 6 km at the poles. It is divided into the boundary layer (from the surface to about 0.5–3 km) and the free troposphere (the rest of the troposphere).

The Sun's rays heat the surface of the Earth, not the tropospheric air directly. Therefore, air closest to the ground is usually warmest. A decreasing temperature profile with altitude is a normal characteristic of the troposphere. However, modifications to this normal profile can influence air quality, as you will see shortly.

The minimum temperature at the tropopause – the boundary between the troposphere and the next region, the *stratosphere* – is due to radiation of heat directly from the tropopause into space. The stratosphere and troposphere both contain broad, fast-flowing 'streams' of air circulating around the world. These are called jet streams, and can change weather patterns.

We study the stratosphere using specialist aircraft, balloons, small rockets and remote sensing from satellite instruments orbiting in space, and find an increase in temperature with altitude due to absorption of solar ultraviolet light by ozone (an important exception to the rule that the atmosphere does not absorb energy from the Sun). This heating via ozone peaks near 50 km at the boundary of this region, the stratopause. This part of the atmosphere is important because the ozone protects the surface of the Earth from most solar ultraviolet light, which can break chemical bonds in living tissue when it penetrates to the Earth's surface.

The ozone layer is the part of the stratosphere that contains the highest concentration of ozone; as shown in the figure, it is found between about 20 and 30 km above the surface of the Earth, though its thickness varies worldwide and seasonally. Ozone concentration in this layer (and the stratosphere in general) began to decrease due to reaction with chlorofluorocarbons (CFCs), but the implementation of the Montreal Protocol of 1987 – which banned the use of CFCs and replacement substances also recognised as ozone-depleting – led to a slowdown in the rate of depletion (CiTEPA, 2012). Tropospheric ozone is increasing, particularly in the northern hemisphere, due to increases in anthropogenic emissions there (EEA, 2011).

Upper layers

Beyond the stratosphere is the *mesosphere*, which is similar to the troposphere in that it lies above a source of heat. Cooling here results in a more dynamic system of winds in the mesosphere, which is therefore relatively turbulent. At the top of the mesosphere, the atmosphere begins to be exposed to the extreme ultraviolet rays of the Sun. This radiation generates species such as atomic oxygen and hydroxyl *radicals* in abundance; these extremely reactive chemical species are present throughout the atmosphere, but in very small concentrations.

The *thermosphere* or ionosphere is by far the most chemically disturbed region of the atmosphere. Here molecular oxygen and nitrogen absorb X-rays. Molecules are dissociated into atoms, violent chemical reactions create new reactive species, and even atoms are ionised by the extremely energetic UV radiation coming from the Sun. This strong absorption of intense radiation by a very tenuous atmosphere causes significant variations of temperature with altitude, time of day and stage of the solar cycle.

Though the thermosphere is very tenuous, having a pressure of less than a hundred thousandth of the pressure at the surface, it is where the aurora (spectacular illumination of the night sky) occurs. It is also responsible for absorbing the most energetic photons from the Sun and for reflecting radio waves, thereby making long-distance radio communication possible. ‘Space’ is conventionally taken to begin at an altitude of 100 km above the Earth’s surface, i.e. in the middle of the thermosphere.

The outermost region of the atmosphere (>500 km) is the *exosphere*, from which gas molecules with sufficient energy can escape the Earth’s gravitational attraction.

In terms of air pollution, our interest is in the troposphere and stratosphere.

SAQ 4

How does the temperature profile differ between the troposphere and the stratosphere?

View answer

2.2 Physical characteristics of the atmosphere

The mixing power of the air and its capacity to dilute pollutants depend very much on the speed of the wind and its gustiness. These characteristics vary widely, both from time to time and from place to place. After pollutants are discharged, the area over which they pass naturally depends on the direction of the prevailing wind.

Consider a gaseous effluent being emitted in a steady stream. If the wind speed is doubled, the pollutant will be dispersed into approximately twice the volume of air so that the concentration at any point is halved. We can say that the concentration is inversely proportional to the wind speed.

The combined effect of forces arising from differences in atmospheric pressure and the Earth's rotation is what causes winds to blow. Above a certain minimum height, and away from atmospheric vortices, the wind blows steadily in a direction at right angles (perpendicular) to the isobars, the lines of equal pressure on a weather map. The wind speed is proportional to the pressure gradient, so winds blowing at the speed calculated on this basis are known as *gradient winds*. The minimum height at which these winds blow, called the *gradient height*, is usually of the order of 600 metres above the ground. Below the gradient height, the wind is slowed down and its direction changed by the effect of friction with the ground, such that it blows more directly towards centres of low pressure and away from centres of high pressure.

Near the ground, the wind is mechanically stirred by objects such as stones, rocks, vegetation, buildings and hills to form eddies. In this way, some of the kinetic energy in the average or mean wind is converted into turbulence and ultimately heat, and the mean wind slows down. The upper layers of air, now moving faster, have to slide over the lower layers and this causes interlocking, an effect that propagates eddies to progressively greater heights. Eddies are also formed during the day when one patch of ground absorbs more heat from the Sun than another. Air passing over it is warmed and, becoming lighter, rises through the air mass as a convection current. Such upward streams, or thermals, add to the general level of turbulence through the mixing effect at their boundaries. The turbulence of eddies, or gusts, often approximates to random fluctuations of air velocity in any direction, which are superimposed on the mean flow.

The viscosity of a fluid expresses how difficult it is to stir: the viscosity of treacle is very much greater than that of water. In air, once eddies are formed, their turbulent kinetic energy is used to overcome the air's viscosity and so it is converted into molecular kinetic energy (or heat). Turbulence would tend to disappear were it not for the fact that new eddies are constantly being formed. The stirring process, due to the unevenness of the ground and buildings, thus maintains a state of turbulence. For convenience of description, the moving mass of air in which this process becomes established is called the *atmospheric boundary layer*.

This is a simple description of a common dynamic situation, but it is often profoundly modified by the way air temperature varies with height, which can have dramatic and far-reaching effects on the dispersion process. This happens for a variety of reasons such as solar heating, radiation cooling at night, variations in cloud cover, etc.

2.3 Dry adiabatic lapse rate theory

The dispersion of air pollutants through the atmosphere depends to a large extent on the speed and direction of the winds, but vertical mixing is influenced strongly by differences in temperature with altitude.

If we assume that the atmosphere behaves like an ideal gas, which is a very good approximation if we keep away from clouds and dust storms, some important general rules of atmospheric behaviour can be found from the basic laws of physics. Following the procedure by which these fundamental results are derived theoretically will help your understanding of some of the mathematics to be used later in deriving air pollution models. It is not necessary to remember this derivation, however.

Conventionally, we begin by imagining a hypothetical parcel of air moving upwards. By 'parcel' we mean a large but unspecified number of molecules of atmospheric gases, all contained within an imaginary system boundary. We know that as we go upwards through the atmosphere, the pressure decreases. Hence, if the parcel of air moves up through the atmosphere it will expand according to the gas laws (i.e. $PV = nRT$, with P being the pressure, V the volume, n the number of moles, R the universal gas constant and T the temperature). Conversely, a parcel of air moving down in the atmosphere will be compressed. The compression or expansion of a parcel of air may also influence its temperature, as you can confirm if you test the temperature of a pump when you inflate a tyre on a bicycle.

If we imagine the hypothetical air parcel moving up or down in the atmosphere, we will expect its temperature, pressure and volume to change. Mathematically, we can represent a small change in temperature by dT, a small change in pressure by dp and so on. Hence, an expression can be derived from the gas laws and the first law of thermodynamics to the effect that:

$$dQ = C_p dT - \frac{dp}{\rho} \tag{1}$$

where

dQ is the heat added to the air parcel per unit mass (in J kg^{-1})
C_p is the heat required to raise the temperature of 1 kg of air by 1 ºC while keeping its pressure constant (this is the specific heat capacity at constant pressure, with a value of 1005 J kg^{-1} K^{-1} for dry air)
dT is a small change in the temperature of the parcel (in K)
ρ is the density of the parcel (in kg m^{-3})
dp is a small change in the pressure of the parcel (in Pa).

On the reasonable assumption that as the parcel of air moves, it neither gains nor loses heat across the boundary with its surroundings (known as an adiabatic condition), we can express the fact that there is no heat loss or gain in mathematical terms as $dQ = 0$. Hence, Equation 1 can be rearranged to give:

$$\frac{dT}{dp} = \frac{1}{\rho C_p} \tag{2}$$

This equation relates the change of air temperature (dT) to the change in atmospheric pressure (dp). A more useful expression would be to relate a small change in temperature (dT) to a small change in altitude (dz), since this is the commonly used relationship. We can express this objective of our calculation as dT/dz.

In order to see how pressure is related to altitude, we need to consider a system as follows. Imagine an increment of thickness dz and density ρ in a column of air of cross-sectional area A. The mass of air in the increment is $\rho A dz$. From Figure 7, it can be seen that the pressure at the bottom of the increment (at altitude z) is equivalent to the pressure at the top of the increment (at altitude $z + dz$) plus the weight of the increment itself.

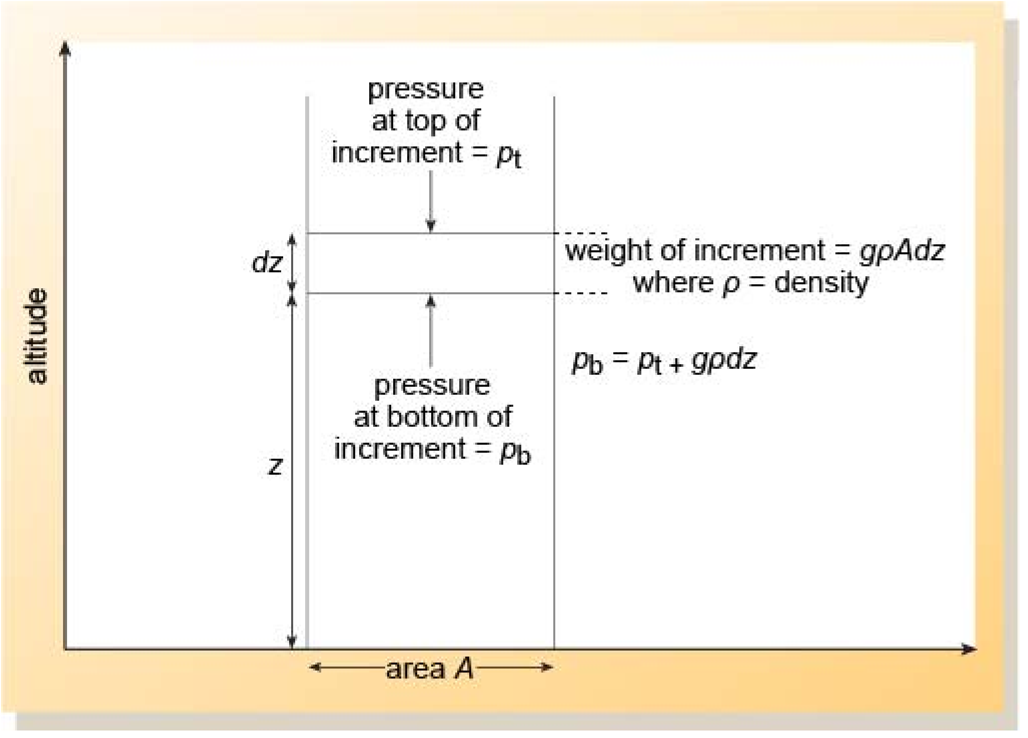

Figure 7 An imaginary section of a column of the atmosphere

View description

Hence, using the terms in the figure:

$$\begin{aligned} p_\mathrm{b} &= p_\mathrm{t} + \frac{g\rho A\, dz}{A} \\ &= p_\mathrm{t} + g\rho\, dz \end{aligned} \tag{3}$$

where

g is the acceleration due to gravity
ρ is mass/volume, i.e. the density of the air
p_b is the pressure (force/area) at the bottom of the increment
p_t is the pressure at the top of the increment.

The pressure change (dp) over the increment dz is therefore given by:

$$\begin{aligned} dp &= p_\mathrm{t} - p_\mathrm{b} \\ &= -g\rho\, dz \end{aligned}$$

We can rewrite this as:

$$\frac{dp}{dz} = -g\rho \qquad (4)$$

The object of this exercise is to derive a value for *dT/dz*, which we can rewrite as:

$$\frac{dT}{dp} \times \frac{dp}{dz}$$

since we already have an expression for *dT/dp* and one for *dp/dz*. Putting all this together, we can write:

$$\begin{aligned}\frac{dT}{dz} &= \frac{dT}{dp} \times \frac{dp}{dz}\\ &= \frac{1}{\rho C_{\mathrm{p}}}(-\rho g)\end{aligned}$$

The expression we have derived therefore becomes:

$$\frac{dT}{dz} = -\frac{g}{C_{\mathrm{p}}} \qquad (5)$$

The value for the acceleration due to gravity, g, is 9.81 m s^{-2}, and the specific heat capacity at constant pressure was defined previously as C_{p} = 1005 J kg^{-1} K^{-1}. Thus:

$$\frac{dT}{dz} = -\frac{9.81 \text{ m s}^{-2}}{1005 \text{ J kg}^{-1} \text{K}^{-1}}$$

and since 1 J = 1 kg m^2 s^{-2}, this gives:

$$\frac{dT}{dz} = -0.00976 \text{ K m}^{-1}$$

Notice the minus sign, which indicates that the temperature decreases as the height increases, and also remember that increments on the absolute temperature scale (K) are equivalent to ºC. The *dry adiabatic lapse rate*, γ, is defined as the negative of the vertical temperature gradient and is therefore stated as a positive number. However, the important result from our calculations is that as a parcel of air moves vertically in the atmosphere, theoretically its temperature will fall by 9.8 ºC for every 1 km rise in altitude and vice versa. This is usually stated as 10 K km^{-1}. Note that the value is given as a positive number even though it represents a negative temperature gradient, because the lapse rate is defined as the rate of *decrease* with height.

In deriving the value for the dry adiabatic lapse rate above, several reasonable assumptions were made. However, the question of whether the air was wet or dry was not considered.

SAQ 5

Before continuing, consider what effect moisture in the atmosphere may have on the value for the lapse rate.

View answer

2.4 Atmospheric stability

Variable heating of the ground from one area to another and over time causes the lapse rate in the lowest few hundred metres of the atmosphere to show marked variations throughout the day. If you were to measure the temperature at various heights in the atmosphere, you would be measuring the *environmental lapse rate*; this is unlikely to be the same as the dry adiabatic lapse rate, which is essentially a standard for comparison.

The difference between the environmental lapse rate and the dry adiabatic lapse rate is an indicator of *atmospheric stability* – which, simply, is the tendency of the atmosphere to resist or enhance vertical motion. This is of importance in the dispersion of air pollutants and hence of air quality. In