Meteorology: an introduction to weather, climate and the environment

Course Preamble

For those who may read these notes on the web, they accompany lectures delivered at the University of Aberdeen. These notes aren't read out during a lecture, they are simply the notes that remind the lecturer what he was thinking about when he was deciding what should go into the course. The course is given with custom PowerPoint slides and, as a student of the course, you are expected to have, or have access to, Donald Ahrens' textbook *Meteorology Today*. See the course introductory document. The structure of the course is determined by Ahrens and the course includes lots of detail given in his textbook but this is supplemented by local context, personal experience and information from elsewhere, most of which can be found in these notes. Notice that there are references on the PowerPoint slides from time to time giving the location of relevant material in Ahrens' textbook. Blue numbers refer to the 6th edition, purple numbers to the 7th edition and black numbers to the 8th edition. If there is no colour then the reference is likely to be the same in all editions. The 12th edition is now available (2018) with an additional author but the price is rocketing and if you can get any of the earlier editions second-hand they will be almost as good and a lot cheaper. Use the *contents* and *index* of the book if you're in doubt where to find material.

Our Aberdeen is the original city of that name, father to some 28 cities, towns and villages in the world called Aberdeen. Our Aberdeen is on the coast of NE Scotland, at latitude 57º N and longitude 2ºW. This is relevant to comments throughout the course on our local climate. These notes are peppered with unexpected facts and the first of these is that Aberdeen is nearer the (north) pole than any permanent habitation in the southern hemisphere is to the (south) pole. Of course there are many places nearer the north pole than Aberdeen but this fact highlights that the hemispheres of the Earth are particularly asymmetric in land distribution, which itself is a big influence on world climate.

Aberdeen is a very good place to study meteorology. Historically there has been an academic interest in meteorology here for over 200 years, from the late 1700s. When the very first national network of seven weather reporting stations was established in Britain to report back to the Meteorological Committee at Kew, so that weather patterns across Britain could be understood, King's College Aberdeen was chosen as one of the pioneering sites. That was in 1868. The station was run by the Professor of Physics (formerly called Natural Philosophy) and was situated in the Cromwell Tower. Photographic records of some instrument readings were taken and the readings were telegraphed south in Morse code. The *Robinson Cup anemometer* that until recently turned on the roof of King's was a relic of that station. Weather reports were returned from the Cromwell Tower until 1947. For 40 years from the beginning of the 20th century (1903-1943) the observer there was George Aubourne Clarke, a man whose *cloud photographs* were known the world over because they became the standard pictures used for identification of cloud types. They have only really been superseded by the rise of colour photography.

Even after George Aubourne Clarke, we continued to make one very small contribution to international meteorology. On the roof of the Fraser Noble Building there was a solarimeter (a solar radiation recorder), which for almost 40 years was part of the National Radiation Network. It was one of the longest-standing electronic solar radiation stations in Britain. Hourly sunshine data were returned to the Met Office and from there went to the World Meteorological Organisation's international archive. The data are still publicly available.

Local weather values for pressure, wind, rain and so on come from the long-standing met station at Dyce and this station has now taken over as the local sunshine recorder too, supplying data in 'real time', which our station never did.

So much for the history. Aberdeen is also a good place to study weather because it has such a varied amount of it. Imagine living in the Steppes of Russia or the plains of Central Canada. The countryside there is flat for as far as the eye can see, and for a thousand miles further. The weather there is more seasonably predictable. Here, influencing the weather at close quarters we have the Grampians to the West, between us and the prevailing winds, giving us some shelter from Atlantic storms and a drier climate than the West of Scotland; we have the sea to the East and a free run to winds from North and South. We may not have extremes of hot and cold but we certainly have variability in our weather.

The Earth's Atmosphere

Overview - intro

From the moment we are conceived, we spend the first 9 months of our lives surrounded by liquid. After birth, we have no difficulty living out of water. We can never take the next step, and live out of the atmosphere. Indeed most of us have difficulty if we stop breathing for more than a minute. The atmosphere is essential to life. It is not just essential to human life. There is hardly a species of living animal or plant in the world that could exist without the Earth's atmosphere, whether they live on land or in water.

The atmosphere is also essential to the quality of life we expect on Earth.

- The atmosphere controls the wide range of climate experienced in different parts of the world;
- the climate controls the great range of physical geography around the world, from swamps to deserts and everything in between;
- the physical geography determines the Earth's hugely varied eco system.
- On an everyday basis, the atmosphere determines the constantly changing visual experience of light, colour, clouds and atmospheric conditions, whether we might get sunburnt when we go out or soaking wet, and so on.

Our course on Meteorology is about this giver and shaper of life - the atmosphere.

Thickness of the Atmosphere

The Earth's atmosphere is a very thin in comparison with the Earth's radius. If the Earth is modelled by a ball 300 mm in diameter (220 mm is football size), most of the atmosphere is within the thickness of a coat or two of paint on the ball. OK, we don't have much feel for how thin a coat of paint is. I'll give you another statistic. We don't have many tall buildings in Aberdeen but a number are 10-storey or a bit higher, such as the Aberdeen College. Take a barometer to the ground floor of such a building and read it. The take the lift to the top of the building and read the barometer again. You'll easily be able to see the drop in air pressure, which is a few mbar in the units I'm going to tell you about. Why has the pressure dropped? Because in going up to the top of the building you've risen above a significant amount of the Earth's atmosphere. That's a bit scary. You can work out for yourself using the result that I'm going to give soon how much air pressure will drop if you go to the top of a building one km tall, which the world's tallest is likely to be in a few years' time.

In everyday life, we experience height and horizontal distance in completely different ways, so much so that our mental model of the world doesn't represent equal distances along and up in the same way. As one illustration, think of this. Suppose we were to lay down over the ground distances that are normally vertical. Take the sea at Aberdeen beach as the baseline and lay out the hills and mountains of Britain horizontally. The entire population of Britain would live in a strip between the beach and the University! Indeed, you would just get Ben Nevis and every mountain in Britain between the sea and here. Think about it. It's a pretty short distance to the beach that a brisk walk will cover in 20 minutes. Ben Nevis doesn't reach to the top of the atmosphere but it does go a significant way up. Air pressure has fallen by one seventh of the total atmospheric pressure by the time you reach the top.

Climb one of the highest mountains in North America and as you approach a summit air pressure has dropped to half. One breath contains only half the oxygen we're used to, and it's bitterly cold too. Modern clothes and climbing accessories make mountaineering easier than it used to be but the lack of atmosphere still gets you, as it always has and always will. (The height at which air pressure has fallen by a half is about 5.5 km. All of Europe's mountains are a bit lower than this except Mt. Elbrus in Turkey). Thinking of going a bit higher? 100 km above us is 'space', for all practical purposes. You could drive 100 km in an hour at 60 mph. One of ESA or NASA's rockets can get to that height in but a few minutes. 'Space' really isn't far away. Bend an A4 sheet of paper longwise around into a cylinder (with its axis on the short side) and the thickness of the paper in relation to the diameter of the cylinder is roughly the thickness of the atmosphere in relation to the diameter of the Earth. I almost rest my case that the Earth's atmosphere is thin.

One final fact may convince any sceptics left. You may know that the average depth of the oceans over the surface of the Earth is a good 2 km. That represents a lot of water. If the atmosphere were liquefied, how deep a layer of liquid would cover the Earth? You will be able to work this out yourself when I've said a bit more about air pressure and you add the fact that liquid air has a density of about 880 kg m^{-3}, a bit less than the density of water. The answer is just about 11 m. That's all. King's College, where we are, would stick up through the 11 m layer into space. Weird. Actually if you cooled the Earth to -200 °C all the air would liquefy and would run down to the lowest levels and create its own seas on top of the existing land and frozen oceans. The frozen King's College would be completely out in space!

A Breath of Fresh Air

You might be forgiven for thinking that in-spite of the comparative thinness of the atmosphere it is still enormous: 5000 million, million tonnes is about the figure. Will a few million tons of undesirable chemicals ever pollute such a massive system? The textbook spells out an interesting argument to show that it can. There are about 10^{44} molecules in the atmosphere; 10^{22} molecules in a single breath. This means, by coincidence, that there are some 10^{22} independent breaths in the atmosphere. Remember this figure. It may sound like plenty of air for a population of less than 10^{10} people on Earth, and it is. Now, take a breath and breathe out. The molecules in your breath will gradually separate and disperse. After some moderate time, say a year, they will be all over the globe, blown there by the winds. On average there are enough molecules in each breath for one molecule to infiltrate each of the 10^{22} independent breaths around the world. Take a deep breath and there is hardly a person alive in the world who hasn't also breathed in one or more of these very same molecules.

Over a lifetime you will breathe out perhaps 10^8 breaths, *deus volenti*. They won't all be completely independent but say you breathe a million independent breaths of air, each one of which contributes a molecule to all the independent breaths around the globe. That, if you think about it, is one million molecules you've breathed that end up in each independent breath around the world. The same argument applies to anyone who's ever lived. There will therefore be about 10^6 molecules (1 million) in each breath we breathe that have already been breathed by any historical character. Choose anyone: Confucius, Jesus Christ, Ghenkis Khan, William Wallace, your great grandfather. Take a deep breath. You are breathing now a million molecules that have been inside their lungs, the very same air that has kept alive saints, despots and our own ancestors. We truly share our atmosphere. Each breath we breathe out supplies about 1 molecule per available breath to others in the future.

[It isn't only the air in the world that is a limited resource. At a basic level the constituents of the Earth are more or less a closed system, largely unchanged for over 4.5 billion years. The water in your drink has probably been in the stomach of a dinosaur. 'Spaceship Earth' is a neat phrase to encapsulate this idea of a finite inventory of elements covering the periodic table that we have available. We have some capacity to change the molecules that these elements make up on Spaceship Earth but there are about 1 million tonnes of atmosphere for every human on Earth and at least 200 million tonnes of water so not even counting the mass of rocks, humans aren't going to make much difference on the scale of a global inventory. Energy is a different matter. There is a continuous supply of energy from the Sun, potentially large amounts of it. It's not infinite, though, either at any moment or in the future but it will last for several billion years. Obtaining useful energy from sunlight and solar heat costs money but we are not limited in future to conserve energy in the same way that we need to look after our store of elements.]

Atmospheric Composition

There is one way in which the previous calculation doesn't give the whole picture. On a long timescale, the atmosphere isn't a completely fixed amount of gas, like the gas put into the tube of a bicycle tyre and held within its walls. For example, when the atmosphere is in contact with the land, oxygen is taken out by breathing animals like ourselves, taken out by chemical processes such as rusting, where iron is converted to various iron oxides (e.g. FeO_2), and oxygen is given back by plants photo-synthesising. Nitrogen is extracted by some bacteria and released by fungal and other decay induced processes. The sea can absorb and release large amounts of carbon dioxide (CO_2), sulphur dioxide (SO_2) and other gases. In brief, the atmospheric composition is *dynamic* (for those who like to collect technical words). At the outer limits of the atmosphere, energetic molecules leak into space but the Earth also sweeps up interplanetary matter such as dust, cometary debris and a huge outflow of material from the Sun called the solar wind. All these dynamic exchanges take place slowly. How slowly is a relevant factor to some important issues that the course will discuss later. For example, it takes decades for CFCs to come out of the stratosphere, which is one reason why it is taking the span of a human lifetime to curb the ozone depletion problem. It typically takes a century before CO_2 that you or I put into the atmosphere is absorbed by vegetation or water, making our ability to do anything about excess CO_2 an issue that will span centuries.

It's history, but perhaps surprising history, that until the last quarter of the 18th century people didn't realise that the atmosphere contained a range of gases, each with different properties. It was just described as 'air'. It's certainly not obvious from everyday experience that air is a mixture. We can't see air, its effectively weightless and we hardly notice it unless there is a wind. Plants need air to live and so do we but it's not at all obvious that we and the plants use different gases within the air. In earlier philosophies, 'air' was explicitly one of the four elements in nature. That idea was completely wrong and thanks particularly to the work of Joseph Priestley in England and Antoine-Laurent de Lavoisier in France, both investigating towards the end of the eighteenth century, the modern appreciation of what our atmosphere is really composed of took shape. Ahrens summarises atmospheric composition in table 1.1 (slide).

- Nitrogen (N_2), Oxygen (O_2) and Argon (Ar) are pretty constant around the globe. As a percentage of the total, these make up almost the entire atmosphere. More than three-quarters of every breath we take is N_2. Now, nitrogen is one of the essential atoms for life. There is nitrogen in every link of our DNA, the DNA that defines our human characteristics. Every cell in our body is a hugely complex chemical factory of proteins, and proteins are made from amino acids every one of which has nitrogen in it. However, none of the nitrogen we're made of gets into us through breathing nitrogen. It all comes from food. And how does it get in to our animal and vegetable foodstuffs? Microbes extract it from the atmosphere. Life is predicated on microbes. Future space colonists take note. Breathing atmospheric nitrogen provides us with nothing directly, as far as our biochemistry is concerned, but we have evolved to expect this gas in the atmosphere. If the nitrogen wasn't there, breathing pure O_2 at normal atmospheric pressure would poison us after a short time. Atmospheric N_2 maintains the expected oxygen pressure and dilutes our waste gas. More subtly, its presence is responsible for the average temperature we experience on the surface of the Earth, a temperature that makes life possible. This matter is touched on much later in our course.

  Atmospheric argon is absolutely useless to the human body, or any other body for that matter. It's chemically inert and not a single molecule inside us contains chemically bound argon. Priestley and Lavoisier and their contemporaries all missed argon. It's another extraordinary fact that such a major component of the atmosphere was not discovered until just over a century ago, by Lord Rayleigh. He won one of the first Nobel Prizes in Physics for his work, in 1904. Argon is more than 25 times as abundant as carbon dioxide (CO_2). Argon makes a very effective fire extinguishing gas and is used in arc welding for keeping other gases from chemically combining with the hot metals being welded. Argon and nitrogen fill incandescent light bulbs.

- Of the rest of the atmosphere: carbon dioxide, CO_2, occupies a small but important place - No CO_2, no plants. Indeed, look in the mirror and you are looking at a lot of carbon atoms. That carbon was once CO_2 in the atmosphere. As you travel to where you are now, look at the trees in the streets, the wood in buildings, the grass and shrubs in gardens, the plastic in the guttering and window frames you passed. The carbon in them was once CO_2 in the atmosphere. CO_2 returns to the atmosphere from the decay of vegetation, from volcanic eruptions, from the breath of ourselves, from burning fossil fuels and wood, from out-gassing of warming oceans. It is estimated that the oceans hold more than 50 times the atmospheric CO_2, a very important fact relevant to long-term climate change. Spare a thought for plants: they need CO_2 as part of their energy generating metabolism but there is only ~0.04% in the atmosphere. We need O_2 and there is more than 20%. That's why Birnam Wood can never walk to Dunsinane, whereas we can. It should be no surprise then that plants are rooted to the ground; they haven't the energy to walk.

I've said that the atmosphere extends up many km but if you separated out all the CO_2 and took it down to ground level it would occupy a layer only 3 m thick. That really isn't very much. If you cooled the CO_2 down so that it froze out (as 'dry ice') then it would form a white layer on the ground less than 4 mm thick. That's 'mm' not metres. Look up at the clouds and compare that with the water in the atmosphere.

Fig 1.4 in Ahrens' textbook shows that atmospheric concentration of CO_2 has risen by more than 15% in the past 40 years, increasing by ~2 ppm per year (ppm stands for 'parts per million'). CO_2 is a greenhouse gas. Greenhouse gases are responsible for keeping Earth's surface warm. CO_2 is not the dominant greenhouse gas. I'll say quite a bit more on greenhouses gases in a few lectures' time.

- Water vapour has the most important influence on life, after O_2. Water vapour makes our weather in large part: the clouds, the fog and the rain. Water vapour assists in transporting large amounts of energy from the tropics to higher latitudes; from the sea, where people don't live, to the land, where they do. Water vapour is also the dominant greenhouse gas that keeps us at an equable temperature in this part of the world.

Ahrens has a section on the early atmosphere of the Earth - read it. The Earth's early atmosphere would have been poisonous to us - hydrogen (H_2), helium (He), ammonia vapour (NH_3), methane (CH_4), CO_2 and no oxygen. This may sound a toxic brew but it wasn't poisonous to the first life on Earth, reminding us that life can thrive in atmospheres that are quite different from the one we have now. Another reminder is that the gases present in the human gut are mainly hydrogen, methane, carbon dioxide and nitrogen, not a mixture we'd survive breathing. Oxygen is produced by plant life and doesn't occur around planets like ours because of any inorganic process. O_2 is considered a signature of life on a planet like ours. If you want a very clear statistic to emphasise this point, then look no further than what we are made of. Two-thirds of the weight recorded when you stand on your bathroom scales is due to oxygen atoms. Almost 60 kg of oxygen atoms are talking to you right now. The presence of O_2 on a cool extra-solar system planet would be world-wide news. O_2 hasn't been found, yet.

[Looking for 'biosignatures' on extra-solar planets has became a serious activity since I first wrote these notes. More certain than just the presence of oxygen would be the presence of oxygen and methane, for the two react (to form carbon dioxide and water) and can't exist in equilibrium. Life on Earth maintains both in our atmosphere. Any non-equilibrium aspect of an extra-solar atmosphere requires some renewal process for one or more of the components.]

There is another feature of the Earth's atmosphere that's so obvious that most people overlook it. Well over 95% of the Earth's atmosphere, the nitrogen, the oxygen and the argon, are pure elements and not compounds. This strongly suggests that the atmosphere we have today formed after the Earth formed. The very early Earth was more than hot enough for compounds of elements to form everywhere. The ground we stand on is a complex of solid compounds; the water in the oceans is a compound of hydrogen and oxygen but the atmosphere is almost all pure elements. Oxygen and nitrogen in the atmosphere can combine into a variety of compounds and indeed combine with other elements. Why haven't they done so? Because the gases that are now our atmosphere came there after the great chemical factory that was the beginning of the solar system closed for business.

Finally, while on the topic of the atmosphere in general, the atmosphere is vital for incubating life on Earth not just because it supplies the gases that animals and plants breath, not just because it brings life-sustaining rain that irrigates the land but because the atmosphere is our shield from the conditions that prevail outside the atmosphere, conditions that modern science has shown are extremely hostile to life. Clouds provide some shielding from the blazing Sun but what I'm referring to here is the shielding that the upper atmosphere provides from UV, which is energetic enough to disintegrate molecules in living tissue, and the mass of the atmosphere which shields us from cosmic rays in general and energetic particle fluxes hurled out by the Sun in particular. We are only just beginning to realise the importance of this aspect of our atmosphere and, for example, how the absence of an atmosphere around a space-ship makes sustaining complex life on-board a real challenge. As far as absorbing the flux of energetic particles hurtling at the Earth is concerned, our atmosphere is as good as living behind a shield of concrete a few metres thick. Space-ships don't come with that specification. It's pretty obvious that without an atmosphere, life would never have got going on the surface of the Earth. The Moon, a body made of broadly similar minerals and at virtually the same distance from the Sun as us, is the obvious example staring at us in the night sky of a body with no atmosphere and no life. Mars is a more pertinent example. It has a very thin atmosphere which nevertheless contains more CO_2 than the Earth's atmosphere, the stuff of life for plants. Are there any plants on Mars? Not even an oasis of primitive ones; Mars is more barren than the Atacama Desert. A contributing factor is that the thinness of the Martian atmosphere fails to provide adequate shielding from the hostile environment of interplanetary space. The hostility of space is discussed in our *Space Science* course (PX2011).

Vertical Structure of the Atmosphere

We all know the atmosphere gets less dense the higher you go. There is less air resistance when running at altitude in Mexico City than at sea level in Athens, Sydney or London. Aircraft flying high can fly faster, or fly at the same speed using less fuel.

$$Density = \frac{mass}{volume} .$$

Why is there a greater density near ground level? Because the air is squashed together more by the **pressure** of the atmosphere above.

What is pressure?

$$Pressure = \frac{force}{unit\ area} .$$

The force in this case is the weight of all the air above.

Units of Pressure

See the details on the slide. 1 Pa (Pascal) is a small unit of pressure. A Newton is about the weight of a tangerine. Spread that weight over 1 m^2 and you have a pressure of 1 Pa. The millibar (mb) is the working unit of meteorologists, equal to 100 Pa. Sometimes the same unit is given its more formal name of the hectoPascal, hPa. Some years ago you would seldom have seen the abbreviation hPa but now it is becoming more common. Another unit for measuring air pressure is the 'torr', the pressure equal to 1 mm of mercury. It's named after Evangelista Torricelli (1608 – 1647), the Italian credited with discovering the principle of the barometer. Torrs are a favourite of those discussing reduced pressures in vacuum systems or in the upper atmosphere.

Atmospheric pressure at sea level is about 10^5 Pa, 1000 mb. That's pretty big. It is the pressure of about 10 tonnes of mass at ground level resting on each square metre. How is it that we're not crushed by the atmosphere? The trick is that we have the same pressure on the inside of us pushing out as is outside pushing in. The two exactly balance, and we sit or walk about as if there wasn't any pressure there at all. There is though, a lot of it. If our inner and outer pressures get out of balance, we soon feel it.

Air is transparent and we don't feel it as we walk about indoors. It's easy to think that there is virtually nothing there. We talk about a bottle or container being empty even though it is filled with air. A modestly sized lecture theatre, such as the one we're typically in for the meteorology lectures, may have a volume of 300 m^3. The mass of air in here is over 300 kg, the same mass as 4 well-built adults. Put another way, if you liquefied all the air in this room and put it in a bath, it would take about 10 people to lift the bath and carry it. Another thought for the day!

I'll add one more paragraph here that links pressure and composition of the atmosphere. Each gas in the atmosphere makes a contribution to the pressure in proportion to how much of that gas there is. This contribution is called the *partial pressure* of the gas. Thus CO_2 is present in about 400 parts per million. If the atmospheric pressure is one bar then the partial pressure of CO_2 is 0.0004 bar. Fizzy drinks like beer, champagne, coke, etc. contain CO_2 at higher pressure (the pressure inside an uncorked champagne bottle is about 5 bar). Pour out the beverage into a glass and the CO_2 will bubble out until the partial pressure above the drink is the same as in the atmosphere. After the initial rush this is quite a slow process and can take hours.

Pressure decrease with height

Weight is caused by gravity. The weight of anything, including a packet of air, is proportional to its mass

$$Weight = mass \times g \ ,$$

where g is the gravitational constant ~9.81 m s^{-2}. Weight is a force and is therefore measured in the units of force, namely Newtons (abbreviated as N). You sometimes see g quoted as 9.81 N kg^{-1}.

Hence at any level you choose in the atmosphere, air pressure is caused by the weight of the air column above that level.

Now you know what the relationship is between pressure and how much mass is needed in the Earth's gravity to cause a particular pressure, you can investigate how much matter there is in the atmosphere. I'll quote you a few figures that I came up with. If the atmosphere were all a ground level pressure, then it would stretch up for just about 8 km. If you collected all the atmosphere into a ball at atmospheric pressure, then that ball would have a radius of 1000 km, or about 1/6.4 times the radius of the Earth; about 1/250th of the volume. If you liquefied the gas in the ball then the molecules of the atmosphere would occupy a ball about 100 km in radius. In terms of analogies of the kind I'll use in the astronomy course, if the Earth were scaled to football size, the liquid atmosphere would be represented by a mapping-pin head. That's about 1/250000th of the volume of the Earth.

[Away from the Earth, little worlds like the moon or asteroids have no air, and hence no air pressure; big worlds like Jupiter have too much air to produce an atmosphere completely like ours. The air pressure lower down in their 'atmosphere' is so great as to compress their atmospheric gas into a liquid. That's a story for our astronomy course.]

Atmospheric pressure falls almost exponentially with height

How quickly pressure decreases with height is important in many circumstances. How high is it best for planes to fly at so they experience less air resistance? The higher the better for decreasing air resistance but propeller driven planes run out of push and all planes run out of oxygen the higher they go, because of the reduced air pressure, and so a compromise is needed. Likewise for athletes.

The relationship giving the change in pressure, P, with height h is:

$$P(h) = P(0)e^{-h/H} \quad .$$

On a graph, the exponential function falls quickly after a fairly straight start. Those who took the first year lab will remember the 'exp' function. In particular how the natural logarithm, denoted *ln*, of the quantity that varies exponentially produces a characteristic straight-line graph. In this case, a plot of *ln* P(h) against h is a straight line.

$$\ln P(h) = -h/H + \text{a constant} \text{ , as shown on the graph.}$$

One consequence of this is that a plot of some quantity that varies with height may be presented as a plot versus the logarithm of pressure, if pressure is used instead of height. For example *ln* P versus T (T standing for temperature) plots are common when plotting atmospheric 'soundings' that will be mentioned later in this section.

Worked calculation example (see slide)

If H = 8 km (a reasonable 'round figure' for the Earth's atmosphere) and the ground level pressure P(0) = 1010 mb, what is the pressure outside an aircraft flying at a height of 11 km?

$$P(11) = 1010\ e^{-11/8} \quad .$$

Therefore using a calculator gives the pressure P at 11 km height as 255 mb.

As an aside, it's worth mentioning that the heights of some of the Cairngorm mountains were measured from atmospheric pressure changes some 200 years ago, before these mountains were surveyed by the Ordnance Survey. Professor Copland, the Professor of Natural Philosophy at Marischal College, and an accomplice were responsible. They simultaneously determined the pressure at the top and bottom and from a known rate of decrease of pressure with height (it's about 10 mbar per 100 m) they could deduce the mountain heights. Their answers were quoted for a long time afterwards.

A picture from 5.5 km high

The photograph was taken by a friend who in 2010 had just come down a bit from a ~6 km peak near Nuestra Señora de La Paz, capital of Bolivia. As mentioned earlier, at 5.5 km high, atmospheric pressure has fallen to half its sea-level value and half the atmosphere is below you.

Why does pressure fall exponentially?

There are two lines to the argument:

1) (hydrostatic) equilibrium requires: *change in pressure* $\propto$ *density*

2) the ideal gas law requires: *density* $\propto$ *pressure*

Hence combining these 2 gives: *change in pressure* $\propto$ *pressure*

This is the condition that signifies exponential change. The change in a quantity is proportional to the quantity itself. Those who have taken our first half-session course will recognise the condition. Others will have to take it as true.

For those who would like to see the derivation of the exponential fall in pressure derived from the ideal gas law in more detail, then look at the blue panel on the meteorology web page and find the supplementary article called '*ideal gas meteorology*'.

Consequences of exponential decay with height

The exponential function decays quickly, so the first consequence is that the atmosphere is close to the ground, i.e. the layer of atmosphere is thin. We've seen how thin. As far as pressure is concerned, the atmosphere gradually fades away. The residual atmosphere at a height of 500 km causes enough drag to affect satellites, though the miniscule pressure there is well into what would be described in the lab as "Ultra High Vacuum" (UHV).

Secondly, the rate of decay is determined by the scaling constant H in our mathematical expression. To see why H is determined by the constants given on the slide, see the notes mentioned above on '*ideal gas meteorology*'. For calculated values of H on the Earth and elsewhere in the solar system see the supplementary note on our astronomy web page on '*planetary ballooning*'. This note also uses the ideal gas laws to investigate how useful balloons might be elsewhere in the solar system. It also says that you can treat H as the height the atmosphere would be if it were all at ground level pressure.

H itself depends on a number of factors but particularly on the molecular weight of the gases concerned (see the slide). The implication is that the rate of decrease depends in detail on which gas you are talking about. The gases with the least molecular weights decay in pressure more slowly. In the lower atmosphere, mixing hides this effect and the % composition is independent of height. Above this region, you might expect the outer reaches of the atmosphere to be of rather different composition to the rest of the atmosphere, and to contain only the lightest gases. This is indeed the case, as the slide says.

Atmospheric constituents separated

Now you have a good idea of how far up the atmosphere extends and how it fades away with height you can get a good idea of how much of each gas there is in the atmosphere by imagining that all the gases could be separated out and stacked up above us. The schematic shows what height in the column all the major or semi-major constituents would occupy. It's quite revealing.

The reference atmosphere

[Fig 1.6 in the textbook shows how air pressure and density decrease together. You would expect this at constant temperature. Fig 1.7 shows the scale on which pressure reduces. Notice that 1000 mb is about sea-level pressure, in round numbers. Pressure has fallen to 50% (500 mb) at 5.5 km altitude and to 300 mb at the tops of the highest mountains. These figures can be seen on the graph given four slides back].

The changes in temperature with height are a different story from the changes in pressure. The lecture slide is similar to Ahrens' textbook figure in chapter 1, although that is drawn for a lower latitude. It shows for our latitude the Cospar ("**C**ommittee **o**n **spa**ce **r**esearch") International Reference Atmosphere, agreed in 1986, which is defined for latitudes from equator to pole. Variations of ±20 K (i.e. ±20°C) or more from this reference are found in temperatures at a given height in the real atmosphere.

When we look at how the temperature changes with height, we find there are distinct layers in the atmosphere and these turn out to be very important. There are a number of technical words associated with this layer structure that are worth knowing.

The troposphere

Let's start at the bottom of the atmosphere. Within any height that you can climb in the world's mountains, you'll generally find that the **temperature decreases** with height at a typical **lapse rate** of 6°-10°C per km. More on lapse rates later. After about 10 km of this fairly steady decrease, the air temperature is typically -60°C, very cold. High wispy clouds are lower than this height in our latitude. They are certainly made of ice, not water droplets - we know because of the wonderful optical phenomena known as the ice particle halo complex, described in the textbook (chapter 4 up to 7th edition; chapter 19 in the 8th edition), that we shan't cover in this course! You can read about it yourselves. This whole region of falling temperature with height is called the **troposphere** ('sphere of change' or mixing) and is the region around the Earth that contains our weather. 80% of atmospheric mass is in the troposphere, whose thickness is less than 0.1% of the Earth's diameter. Convection currents, packets of warm air heated by the Sun and the warm ground, rise up, expanding as they experience lower pressure, and cooling as they do. Then they hit an apparent barrier, called the **tropopause**.

The stratosphere

What is this barrier? At the tropopause an **isothermal layer** begins, about 15 km thick, in which the temperature is approximately constant at around -60°C. Rising air comes to a halt here because as it tries to rise its pressure decreases, it cools, finds itself denser than its surroundings and sinks. More on this later. It is essentially because of this effect that the weather with all its circulation is confined to the troposphere. Look at the top of an anvil cloud and you will see the effect of the tropopause shown graphically. The towering expansion below has come to a halt and the cloud spreads out horizontally, almost as effectively as if there were a glass lid on the lower atmosphere. The isothermal layer is the base of the **stratosphere**. Above this layer, at a height of 25 km or so, the temperature starts to rise. The pressure, remember is continuing to fall and is only around 30 mb at 25 km. A world record parachute jump from 31 km was set by Joseph Kittinger in 1960 but as the risk-taking free-faller said at the time about the lack of atmosphere "outside (the capsule from which I jumped) it might as well have been cyanide" and he needed to wear the next best thing to a spacesuit. The parachute record was broken in 2012 by Felix Baumgartner who leapt from 39 km. Above 25 km the temperature continues to rise with height, sometimes reaching as high as 0°C before there is yet another change at the **stratopause**. This occurs at a height of about 50 km and pressure of 1 mb. The rise in temperature with height is called a **temperature inversion**, because it is the other way round to what we are used to in the troposphere.

Heating in the stratosphere is largely supplied by the absorption of UV by stratospheric ozone. This ozone is crucial to us. You probably know that it saves life on the surface of the Earth from being exposed to UV. It also provides the temperature inversion layer that keeps life-giving water vapour in comparative close proximity to the ground. Stratospheric heating requires that there is enough ozone to intercept much of the UV incident in the stratosphere. You can't see the ozone absorbing UV because ozone is transparent to visible light. However, what is happening can be shown in visible light by me simply holding this sheet of paper in front of the projector beam. Now the visible light is prevented from penetrating to the screen because it is absorbed and scattered by the paper. Likewise, UV is prevented from reaching the ground by ozone, absorption being the main effect. A glass sheet held up by me would not absorb any visible light; it lets the image through just as say nitrogen in the atmosphere lets through UV. It took a while before people realised what was going on because the ozone is the next best thing to invisible and so is the UV it is absorbing. Another example of absorbing invisible radiation is one you can experience yourself. Simply hold your hands in front of a nice glowing fire. Your hands absorb IR in this case, and you can feel them heat up.

The mesosphere and above

Above 50 km, air pressure and density are too small for their absorbing effect to provide enough heat to make much difference. The stratosphere comes to an end at the **stratopause**. Above it temperature falls again in the **mesosphere** (middle sphere), until yet another boundary is reached at around 90 km, known as the **mesopause**. Temperatures there are around -80°C and the pressure is about 0.01 mb. When you see 'shooting stars' at night, 'meteorites' to give them their more scientific name, then you are usually looking at objects burning up in the mesosphere. The slide shows noctilucent clouds, a phenomenon particularly visible from latitudes similar to Aberdeen but which many people have never noticed. These delicate, wispy, light blue clouds can be seen an hour or more after sunset or before sunrise in a clear summer night's sky, usually between mid-June and mid-August. They occur near the mesopause, close to 90 km, which is astonishingly high for clouds since even the highest clouds of normal weather are at the tropopause, only some 10 km high. A former colleague, Michael Gadsden, spent many years researching the nature and cause of these clouds and with a collaborator wrote the only book on them that I know about.

Above the mesopause is the **thermosphere**, a complex region receiving tremendous energy from the Sun but exceedingly thin in molecules by ground-level standards. The heating comes from intercepting very energetic UV from the Sun. In addition many atoms are ionised and accelerated by the Earth's electric and non-uniform magnetic fields, travelling many km before colliding. Temperatures rise with height to hundreds of °C. There is no effective mechanism for dissipation of energy. This is the region the aurora lives in. Finally, at about 500 km, some molecules and ions are energetic enough and travel far enough between collisions that they can potentially escape. This is the **exosphere**. Helium is probably the dominant gas at ~500 km and temperatures are ~1500 K; H is dominant above ~3000 km.

In brief, the structure of our atmosphere is complex, almost bizarre. The weather, by and large, is at the bottom. The structure above holds it in and the Sun, 150×10^6 km away, drives the weather. There is a lot more going on than I have said so far, but that is for later. It's good for us that it is like this. If you want to cook potatoes in a pan – you don't fill the pan with water and apply a blowtorch to the top. You heat moderately from below. In nature, the blowtorch is out there and, fortunately for us, we can lead a tolerably pleasant life at the bottom of the pan, without being overcooked.

Radiosondes and their sensors

How do we know about this complex temperature structure? In the past it was through instruments carried aloft by balloons and, for the very high atmosphere, by measurement made using rockets. Nowadays little is done from rockets but satellites look down from above and through measurements made in the infra-red and microwave, water vapour distribution, clouds, winds even and atmospheric temperature profiles can be deduced, though vertical temperature distribution is only inferred indirectly. More direct measurements are also made using **dropsondes** containing instruments taken very high by plane and dropped from above. Balloon borne instruments still play an important role. Temperatures are measured by balloon soundings up to about 30 km. **Radiosondes** are balloons let off at specific times of the day, usually from traditional centres, to **sound** the atmosphere. They transmit back values for *temperature, pressure* and *humidity* – all measured electronically. [I haven't said yet what humidity measures, but you already know]. Logging height versus time gives the rate of ascent. Tracking the balloon (e.g. with radar) enables the vertical distribution of winds to be found because the balloon will travel with the local wind at each height. A wind-tracking balloon is called a **rawinsonde**. Some sondes have equipment that will give information about atmospheric chemical composition, for example the ozone concentration. Eventually the balloon bursts and the instruments parachute to the ground. Often they are not recovered.

Slides showing typical sensors and telemetry equipment

Slide showing the location of radiosonde stations

The discussion on the constituents of the atmosphere continues with a whole section devoted to ozone. This is a hot topic in atmospheric science and until it was displaced in recent years by 'climate change' it was probably the aspect of the atmosphere that got the most media attention.

The end of the first section on 'the atmosphere'

Here's an experiment you can do 'at home'

You'll need a bottle of good wine, or a decent sized bottle of water if you prefer, some walking shoes and a few friends to help. Take the bottle on a walk up the highest hill you can, preferably one over 1000 m. Share out the wine/water at the top, down to the last drop, and then securely re-seal the bottle, trapping air at hill-top pressure. Sparkling wine is unsuitable since the bottle is heavy and can't be re-sealed. [Hill walking requires a clear head so don't over indulge in wine]. Return home.

Now fill a basin with water and get the bottle you sealed on the mountain top and invert it with its neck underwater *before* you unseal it. Then release the seal. Water will immediately enter the bottle, the amount depending on how high you climbed. That water represents the lack of air you experienced on the hill top. If you shake out the bottle, re-seal it, re-immerse it and proceed as before you'll find very little water now goes into the bottle, for the pressure of air inside is now almost the same as the pressure just under the water surface. It's slightly better to have a second similar bottle and convince yourself before opening the hill top bottle that little water enters when you seal an 'empty' bottle in a room and then unseal it upside down underwater.

In the unlikely event that you climbed up 5.5 km in a serious piece of mountaineering, the mountain top bottle would have half-filled in the first instance. Even after a modest climb the hill top bottle will visibly take in water, demonstrating that air pressure does decrease noticeably with height. As the lecture said, about 1% for each 100 m climbed but you don't need to take my word for it.

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