Atmospheric Stability & Cloud Development

This section looks at the basic cause of stability and instability in the atmosphere. Why some clouds are like tall towers, others huge flat sheets. We shall look at what conditions are favourable for cloud development and, in passing, how pollution behaves when fumes are emitted from chimneys. The stability of the atmosphere is intimately connected with the *lapse rate*. How this comes about is a central idea that governs the weather we experience and hence is a central concept in weather forecasting. It will take some serious thought to understand. We'll put in some numbers, too, so you can see how the ideas work in practice. The topics here are mainly covered in Ahrens' textbook in chapter 6 of the 8th edition, with some air pollution topics from chapter 18.

Stability

What is meant by *stable* or *unstable* conditions? Stability is a concept that describes what happens when a system is disturbed. When a ship is tilted sideways by waves, it returns to its upright position quickly, because it is stable. A ball at the bottom of a bowl is stable; after a slight push, it rolls back to its initial position. A big sheet of cloud sitting at the 1500 m level is usually stable. It neither rises when disturbed by updrafts from below nor sinks due to downdrafts from above. For example, an updraft may try to push up a section of the cloud but it will quickly sink back to its previous height. Likewise for a downdraft.

Neutral equilibrium is the special case when a change is neither resisted nor encouraged, e.g. push a pencil along the table. At every position, the pencil is in neutral equilibrium.

Unstable equilibrium. Try balancing a pencil on its point. The slightest disturbance and it moves even further from its equilibrium position. A parcel of air in unstable equilibrium will keep rising when given a slight push from below.

The Players

We've already met all the concepts that are central to discussing atmospheric stability:

- *Pressure* excess inside a parcel of air causes it to expand against the inward pressure of the surrounding air.

- *Density* is mass per unit volume. Density changes inversely as the volume of an air parcel (whose mass is constant).

- *Temperature* is measured in Kelvin when used in equations, or Celsius for everyday use.

- *Moisture content*, commonly measured by relative humidity or dew point. The absolute value of the water content is not usually the most important issue but its value compared with saturation vapour pressure. That is why *relative humidity* is more relevant than specific humidity.

Floating in air

When a stone is thrown into water, it sinks because its density is greater than that of the fluid that surrounds it. When a helium balloon is let go, it rises because its density is less than the air that surrounds it. What is happening in both cases is that the objects in the fluid have two forces on them: their weight, which is of course downwards, and an up-thrust, which is of course upwards. If the downward force exceeds the upwards force, then the object will sink; of course if the upwards force is the greater, then the object will rise. So far, that's pretty obvious.

It was Archimedes stroke of genius to realise that the up-thrust was produced because the object, stone or balloon, was displacing the fluid from the volume it occupied. The up-thrust is therefore created by the volume of the object times the density of the surrounding fluid. [In standard symbols, if V is the volume of the object, ρ_{fluid} the density of the fluid, then the up-thrust is $V\rho_{fluid}g$]. Now the downward force is just created by the volume of the object times the density of the object [$V\rho_{object}g$]. Hence the statement in the paragraph above follows, namely that whether an object floats or sinks depends on its density relative to that of the fluid it is immersed in.

What happens if the 'object' is just a parcel of air, immersed in surrounding air? Exactly the same applies. There's only one question to ask: "is the density of the air parcel greater than or less than that of the surrounding air (or perhaps equal to it)?" Answer that and you can tell if the parcel of air will fall, rise or stay put.

Rising and Falling

There is a complication with air parcels that there certainly isn't with an object that keeps its size when it moves up or down. Suppose your air parcel is less dense that the surrounding air. As the air parcel rises, it moves up into less dense air because air higher up is always at a lower pressure and density that the air below. So far, so good. Will it rise up and come to a halt? Perhaps, *but* the complication is that the parcel also expands because the pressure exerted on it is less higher up, so the parcel, too, becomes even less dense on rising. Is the parcel going to quickly come to a halt or will it keep rising because its density is always a bit less than the surrounding air? Sometimes one thing happens, sometimes the other. We'll see how to work out which outcome will happen in a given situation.

If the density of the parcel is less than that of the new air it has risen into, the parcel keeps rising and it is said to be *unstable*. If the reverse happens, it stops rising quickly and is *stable*.

Summary: stability depends on relative density between air and its surroundings. Density of air, though, is not easy to measure and meteorologists have exploited the connection between density and temperature. This is useful because temperature is much easier to measure. What is the connection and why do meteorologists keep going on about temperature? We'll see.

Density Depends on Temperature

Changes in parcels of air are governed by the *gas law,* which relates changes in pressure (P), volume (V) and temperature (T). The *ideal gas* is the simplest physical model of a gas. Volume, pressure and temperature are linked by the '*ideal gas law*'

$$PV = nR\,T \ .$$

R is a fundamental physical constant (called the 'gas constant' with a value of 8.31 J mol^{-1} K^{-1}) and n is also a constant for a given parcel of air, effectively measuring the amount of air in the parcel. (Chemistry students will recognise n as the number of 'moles', with 1 mole occupying 22.4 litres at standard temperature and pressure).

The term nR in the relation above is just a measure of how much gas there is in the given volume V. It could just as well have been written as M**R**, where M was the mass of gas and **R** the gas constant per kg. Written that way, it's obvious that if you divide both sides by V then on the right-hand side you now have the ratio M/V, which is just the mass per unit volume, namely the density ρ of the parcel of air. Hence, written alternatively, the gas law expresses the relationship:

$$P \propto \text{density} \times T.$$

In other words, warmer gas has less density **at a given pressure**; cooler gas has a greater density. This relationship gives the key connection between density and temperature for parcels of air at the same pressure, i.e. the same height. The proportional sign can be made into an 'equals sign' if you use the right units. From the discussion above, it's clear, I hope, that $P = \rho\mathbf{R}T$, where ρ is the gas density and **R** here is the 'per kg' gas constant of 287 J kg^{-1} K^{-1}.

Adiabatic changes

We are going to be looking at air expanding as it rises, or compressing as it falls. How much expansion (which is a change in volume) occurs depends on how the expansion takes place. Possibilities might be volume change at constant temperature, volume change at constant pressure or something else. The usual assumption in meteorology is that parcels of air are sufficiently big that no significant heat gets in to a parcel as it expands, or no heat leaks out when it is compressed. Such a change is called *adiabatic*. Adiabatic changes are governed by

$$PV^{\gamma} = \text{constant}, \qquad \text{with } \gamma \sim 1.4 \text{ for air.}$$

Using this relationship along with the gas law (written as $P = \rho\mathbf{R}T$) we can convert the change in pressure with height to a change in temperature with height. For those who would like to see how this is done, then look at the supplementary note called '*ideal gas meteorology*' in the blue panel on the left of our meteorology web page. The result tells us what happens to the temperatures of air parcels as they rise and fall, and that in turn is related to density changes and hence their stability.

The adiabatic assumption is pretty reasonable in the circumstances because heat flow is a very slow business whereas air subject to changes of pressure adjusts its volume very quickly. If adiabatic change is new to you I'll add another example. I think 'everyone' knows that sound waves in air involve changes in pressure propagated at typical frequencies of hundreds of times per second. As the air is compressed and rarefied in the wave there is no time for heat to flow from the volumes momentarily at higher pressure to those at lower pressure. Hence the pressure changes must be adiabatic and you would expect the constant γ to appear in the formula for the speed of sound in gases. It does. The great Isaac Newton was the first to deduce a formula for the speed of sound but he made a mistake (not his only mistake!) of assuming that the pressure changes happened at constant temperature, so his formula was a bit in error. That was a digression.

Adiabatic Lapse Rates

We can get the flavour of how the ideas above work together without having to follow the maths in detail. Look at the ideal gas law. Supposing the parcel of air moves up from the ground to where the pressure has dropped by 10%. **If** in doing so it were to expand by 10% then PV will remain constant and hence from the gas law the temperature won't change at all. In fact this doesn't happen. What happens is that the volume V expands by less than 10%. Hence the left-hand side of the gas law gets smaller and so the right-hand side must get smaller too. That means the temperature drops. By how much less than 10% does the volume expand? The adiabatic condition tells us. In an adiabatic change $PV^{1.4}$ remains constant and hence $V^{1.4}$ changes by 10% which, after a few button presses on the calculator, means that the volume increases by 7.8%. Hence, with a little more help from the calculator, the product PV drops by 3% and so the temperature drops by 3% of its absolute value, i.e. its value in degrees K. If the temperature on the ground was at 280 K (7 °C), a round figure representing a typical temperature here over the past few months, it will drop by 8.4 K to 271.6 K or to -1.4 °C. A change of 8.4 K is of course exactly the same change as 8.4 °C.

To convert this into a lapse rate you need to work out what height the pressure drop of 10% corresponds to. From chapter 1, the pressure at height h, denoted $P(h)$, $= P(0)e^{-h/8}$, where h is in km. A pressure drop of 10% is equivalent to $P(h)/P(0) = 0.9$ and this gives $h = -8\ell n 0.9 = 0.843$ km or 843 m. So the lapse rate is 8.4°C in about 840 m or 1 °C per 100 m, exactly what the textbooks say. I hope the numbers above convey the gist of what is happening.

You may find it curious that the temperature changes at all when no heat is lost from the parcel of air. What is happening is that the parcel of air has to push against its surroundings as it expands, moving them out of the way to allow for the expansion. It loses some of its internal energy in doing this. The result is a cooling.

Meteorologists concentrate on the temperature changes as a parcel of air rises or sinks. The change in temperature with height when adiabatic changes are occurring is called the *adiabatic lapse rate*. It is a bit different for dry and moist air, because when moisture condenses as the temperature drops, latent heat comes out to reduce the temperature drop.

Thus we have as useful working figures:

- The dry adiabatic lapse rate is about 10°C per 1000 m

- The moist adiabatic lapse rate is about 6°C per 1000 m

Table 6.1 p 141 (8th ed'n) shows how the moist adiabatic lapse rate actually depends a bit on pressure and temperature. 6°C is typical at 0°C and 2 km in height, the sort of height that parcels of air reach their dew point and start to form clouds.

A nice example that makes the decreasing temperature with height visible can be seen on some winter days. You are in a valley. The temperature is 1°C and the day is damp. The ground around is wet with puddles from recent sleet but no snow is lying. Look up to the hills and you see the snow-line, less than 200 m above you at a constant height all round the valley.

The snow line more or less picks out the 0°C contour. If the forecasters have got the height of the 0°C contour too low by just a couple of hundred metres then they will wrongly forecast snow for the villages in the valley. It can be tricky to get snow forecasts right in this situation.

Atmospheric Temperature Profile

The actual temperature profile above you depends on the history of the air present. It can be measured by balloon-born thermometer. The result is called *the environmental lapse rate.* This lapse rate is one of the most important properties of the atmosphere you can measure if you are interested in predicting the weather. Hence the number of radiosonde ascents that meteorologists make. The slide shows it at 5°C per 1000 m. Note that lapse rate is the slope of the profile, **measured from the vertical** on the standard graph.

Stable Air

When is air stable? To determine the stability, compare the environmental lapse rate with the adiabatic lapse rates. For absolutely stable air, the environmental lapse rate is less than either adiabatic line.

Why is this? A parcel of air at any height when pushed upwards will change its temperature by the appropriate adiabatic lapse rate (dry or moist). The slide shows that this will involve a greater cooling than occurs in the environment. The air parcel will find itself colder and denser than its surroundings. It will therefore sink back, effectively resisting the upthrust. The pieces of our earlier discussions should now all fit together.

A temperature inversion means a rise of temperature with height. Temperature inversions are clearly associated with an absolutely stable atmosphere.

One way of forming stable conditions therefore occurs when the lower air layers are preferentially cooled, such as by cooling of the ground at night by radiation loss. Cloud or fog close to the ground remains there. Smoke and steam from chimneys tends to *fan out* horizontally. Stable conditions, particularly a temperature inversion, puts a cap or lid on vertical motion.

Conditional Stability

Air that has a lapse rate in between the moist and dry adiabatic lapse rates is said to be *conditionally stable*. If the air is *dry*, it is *stable*, if it is *moist* it is *unstable.*

Moist air is unstable because an upthrust that pushes up an air parcel a little will cause the temperature to change with the moist adiabatic lapse rate, which is less than the environmental rate. The adiabatic cooling is therefore less than the actual cooling of the surroundings and the parcel finds itself warmer than its surroundings. It therefore continues to rise and is unstable as far as height is concerned. If all the water in it condenses, then the air becomes 'dry' and it will stop rising.

Likewise, if conditionally stable moist air were pushed down from above it would warm less than the surrounding air and so would find itself cooler than the surroundings and hence would continue to sink. This would be true provided the air remained moist but in practice if the air sinks, it warms, its humidity reduces and it becomes dry. If the atmosphere is conditionally stable, as it usually is, you can expect moist air to rise and dry air to be stable [passim: relevance of lapse rate to balloonists. If air is unstable, it is typically rising on a fine day and it is harder to return to ground to 'punch through' unstable layers. If air is stable, it may need a lot of lift (and hence fuel in a hot air balloon) to rise.]

Unstable Conditions

All effects that heat low level air tend to produce instability. Absolutely unstable air is air where the environmental lapse rate is greater than even the dry adiabatic lapse rate. Unstable air is prone to vertical motion. Thick cumuliform clouds grow when the rising air within them has saturated and is ‘moist’ in this context.

Stability conditions change during a day, particularly if there is little wind and hence little mixing. You can see that with solar heating of the ground, the conditions for instability are encouraged as the day progresses and afternoon cumulus are a very common result.

Instability encouraged

One general rule is that a rising thickness of air tends to become less stable and a subsiding thickness of air more stable. The basis of this is that as air subsides it compresses and occupies a narrow range of heights. Hence the top of the layer *subsides* a greater amount than the bottom of the layer and therefore warms more than the bottom. This reduces the temperature difference across the layer and increases its stability. You may rightly point out that the reduced temperature difference occurs over a reduced layer thickness so how do you know that the lapse rate is actually reduced? The example figures in the next paragraph show that it really is: the temperature difference is reduced even more than the thickness difference.

The reverse happens to a rising slab of air, which stretches out and acquires a larger lapse rate and hence less stability. A numerical example shown on a diagram in the textbook makes this clearer. The corresponding diagram is on the slide. The figures behind the diagram are more or less as follows. A parcel of air 100 mbar thick that stretches from ground level where the pressure is 1000 mbar is imagined lifted up so that its lower pressure is at 600 mbar and its upper pressure is at 500 mbar. How much cooling takes place at the bottom and top of this layer? We need to know the heights involved. Again, we’ll use the relationship between pressure and height given in the first chapter, namely that the pressure at height h, denoted $P(h)$, $= 1000e^{-h/8}$, where h is in km. The heights involved are: 843 m at 900 mbar; 4086 m at 600 mbar and 5545 m at 500 mbar. It’s clear that the layer at ground level that was 843 m thick before being lifted has been stretched out after being lifted to (5545 - 4086) = 1459 m thick. I hope you can see where this argument is going.

Suppose the air was initially very stable and all at 15°C, making its lapse rate zero, then after lifting and cooling at the dry adiabatic lapse rate, the bottom has cooled by about 40°C to -25°C and the top has cooled by 47°C to -32°C. The top has been cooled more because it’s been lifted by more. There is now a 7°C temperature difference over a thickness of 1459 m, equivalent to a lapse rate of 4.8°C per 1000 m. This isn’t enough to convert a very stable layer to an unstable one but it is getting close. Had the ground level layer had a lapse rate of only 2°C per 1000 m, still very stable, after lifting it would be conditionally unstable. You can see that to work out all this detail needs no more facts and figures than you already know!

The lifting effect is even more pronounced if moist air near ground and drier air aloft is lifted. The drier air cools more quickly than the moist air, hence increasing the lapse rate of the whole layer and making the air less stable. This is the basis of *convective instability*. Convective instability is usually at work in thunderstorms associated with vigorous cumulonimbus clouds.

Fumigation and Dispersal of Pollutants

With warming of the ground during the day and the steepening of the environmental lapse rate, unstable conditions develop near the ground. With stable conditions above, the worst possible conditions exists for dispersing chimney stack fumes, and they tend to descend to any conurbation around the plant. This condition is called *fumigation*.

Looping

In absolutely unstable conditions, the plume rises and falls unstably. If there is not too much wind to blow away the fumes, the plume follows a *looping path*. Remember that instability applies to both upward and downward motion of air parcels.

Coning

Occurs in neutrally stable conditions - the plume spreads equally up and down by dispersion without turbulence.

Lifting

With a temperature inversion below, or at least stable conditions, there is no downward mixing of the plume and it rises, ideally into unstable air so that it gets carried aloft as quickly as possible. It then becomes 'someone else's' problem' - that's the idea! The atmosphere is large but, aerosol particles eventually come to ground in rain or may dissolve in rain water. So out-of-sight is not necessarily out-of-mind.

Cloud Development

Fig 6.15 shows 4 main ways clouds develop. We are going to look only at the first - the origin of cumulus clouds.

Cumulus Clouds

Convective cells are induced by local heating of the ground. This gives rise to unstable air. Air rises and cools, until it eventually reaches the dew point. Between the clouds, air sinks, warms and evaporates any moisture, leaving a clear space. The downward motion is encouraged by evaporation at the edge of the cumulus, which cools the air and causes it to sink. As it sinks, it warms and dries and encourages further evaporation at the edges of the cloud.

Figure 2 in the focus on convective cloud bases in the textbook shows a rising bubble of air. While rising, it remains everywhere warmer than its surroundings, until eventually it reaches the temperature of its surroundings at ~ 2000 m and stops rising. The cloud base forms when the air reaches its dew point. When is this?

Dew point revisited

The dew point is the temperature at which the water vapour pressure in the air equals saturated water vapour pressure. Calculations at the end of the section of the course on atmospheric water to find the dew point went along these lines: 1) find the water vapour pressure in your air from the humidity and temperature 2) find at what temperature this vapour pressure is the saturated vapour pressure and you have the dew point. There is a hidden approximation in this method. The approximation is that when the air is cooled to the dew point any change in the pressure of the water vapour is ignored. In reality the water vapour pressure will drop, a bit. The ideal gas laws tell you that. For example, suppose the initial temperature is about 20° C and the air cools to 10° C then to find out the pressure change we need to put the temperatures in degrees Kelvin and remember that the gas law says that a constant volume of gas (say that in a room) the pressure drops by the same fraction as the Kelvin temperature drops. In this case 20° C is 293 K and 10° C is 283 K. Hence the drop in pressure is by a factor 283/293 = 0.966. This isn't much and for practical purposes the dew point calculated by assuming the water vapour pressure stays the same is a good enough answer.

With parcels of air rising up to a cloud base we can't say that the water vapour pressure stays constant in the parcel. For a start, the volume of the parcel doesn't stay constant. We know that the parcel expands adiabatically. Its pressure drops and hence the pressure of all its component gases drop, including the water vapour within it. The dew point for that parcel will therefore drop too, because the temperature at which the water vapour pressure equals the saturated vapour pressure must be lower if the water vapour pressure itself is dropping. Putting in the real numbers, the pressure drops by 10% for every 1000 m the parcel rises and from the relationship between dew point and temperature you'll find the dew point drops by almost 2° C. The supplementary notes on 'ideal gas meteorology' to be found on the blue panel in our meteorology web page show how to derive this figure. You can optionally read these. We'll use the rounded figure of 2° C km^{-1} for the drop in dew point with height.

Cloud base

As an air parcel rises, from the cooling alone you would expect the air temperature to approach the dew point at 10°C per 1000 m of rise. However, as the previous slide said, the dew point recedes (i.e. drops) at about 2°C in 1000 m. The dew point is a moving target. What therefore happens as a result of both the falling temperature and the falling pressure of a rising parcel of air is that the 'dry' air temperature (no condensation) approaches the dew point at only 8°C per 1000 m. Put another way, air temperature and dew point approach each other at only 1° per 125 m height difference. Hence the rule for the *lifting condensation level.* The height in metres (H_{metre}) of the cloud base:

$$H_{metre} = 125\ (T - T_d)$$

where T_d is the dew point on the ground.

With this relationship, you can predict the cloud base height if you have a wet and dry bulb thermometer from which you can find T and T_d. The slide shows an example. You can also use the relationship the other way around. For example, suppose on a sunny summer day the convective cloud base is at 2000 m, well above the tops of Scotland's mountains. If you're in the Highlands, this isn't too difficult to estimate. The relationship implies that the dew point on the ground is low, in fact some 16º below the surface temperature. The likelihood is of a dry day and if it continues through the night, a dawn with no dew on your tent.

Cumulus Cloud Development

Refer to Fig. 6.18, shown in the slide of the *graphic summary of condensation*.

Rising air in the cloud remains saturated and temperatures fall at the moist adiabatic lapse rate. The cloud stops developing when the temperature of the top of the rising, cooling air reaches that of its surroundings. This may happen if the cloud top reaches a stable layer, such as might be formed by sinking air above. However, raising an air layer generally makes it more unstable and this *convective instability* can lead to clouds reaching the tropopause in a pretty short space of time, creating Cb clouds, and thunderstorms at appropriate latitudes.

Imagine a fine, sunny summer afternoon. You can see for miles; the blue of the sky seems particularly intense and billowy cumulus clouds drift across the skyscape. As evening follows afternoon you look up and the billowing cumulus have shrunk and thinned out. A little later they have disappeared altogether, leaving a hazy, pale blue sky that promises a sight of the evening stars when darkness sets in. Why shouldn't you be surprised? You could even have impressed your friends by predicting it would happen. The fading of the cumulus is visible evidence that the evaporation and convection that creates them in the first place is driven by the warmth of the sun. As the driving force sinks towards the horizon and the ground turns its face away from the sun, the convection that feeds the clouds fades out too. There can hardly be a clearer example that the heat of the sun creates the clouds, the ever-changing component of our landscape and our weather.

Formation of Cirrocumulus Cc

A thicker layer of high level cirrostratus Cs often breaks up into cirrocumulus cells, well seen if you are flying high enough in a long distance aircraft. The reason is this:

The top of cirrostratus is exposed directly to space. It looses heat faster than the bottom of the layer, which is facing the ground or a lower cloud level. The lapse rate across the cloud layer therefore increases and finally the layer becomes unstable. Convection currents begin and cumulus formation starts. In the down flowing part of the convection current, the air is warming and this will tend to evaporate the moisture within, creating clear gaps between the convection cells. The layer of stratus soon breaks up once this process begins.

You may say that the top of the original layer is also facing the Sun, so shouldn't it get heated. It will, to some extent, but high clouds with comparatively little in the way of trapped aerosols let through most of the radiation falling on them. The heating effect loses out to the radiative cooling.

End of Atmospheric Stability

JSR