Condensation

Dew and frost on the ground, fog a bit above ground and clouds in the sky are all the effects of condensation. This section is about condensation, the sky and satellite images. The average cloud cover over the Earth is some 62% and is fairly stable. That said, of course some clouds are very thin and whether a portion of the sky is covered or not isn't completely cut and dried. The issue is actually very important because cloud cover affects the global energy balance and hence cloud cover changes have the potential to affect global warming. On the one hand, clouds reduce the Earth's average temperature by reflecting away incident sunlight but on the other hand they increase the average temperature by intercepting long-wave re-radiation from the surface. The net effect is a cooling, reducing the energy flux at the Earth's surface by about 20 W m^{-2}. This lowers our average temperature by about 4°C. The topics here in this largely descriptive section are covered in Ahrens' textbook in chapter 5 of the 8th edition.

Condensation Nuclei

At night, the ground cools before the air above it and, when the temperature falls below the 'dew point', of course dew forms. The dew point can well be below 0°C (because even ice has a vapour pressure). If the ground cools to a dew point that is sub-zero, hoar frost forms by *vapour deposition,* of solid from vapour. With both dew and frost, the condensation takes place **on** something. In the atmosphere, water droplets don't form on nothing, water molecules in the atmosphere all arriving spontaneously at the same point. That's *not* how it happens. When clouds are formed, water condenses onto **condensation nuclei**.

There are generally plenty of these nuclei about, due to natural causes such as dust, volcanoes, sea-spray and smoke, stirred up by the wind. Man's activities around industrial sites usually provide many more. Several years go the national news featured pictures of swirling, dense fog persisting for months over thousands of square km in the Far East, originating from huge clearing fires in Indonesia. Close to home, cities in Britain must abide by the most recent 'Clean Air Act' which allows Local Authorities to declare smoke controlled areas. In these it is forbidden to emit smoke from a chimney and hence houses with fireplaces can't burn the coal the fireplaces were designed for. Aberdeen is such an area. It is only the older members of the population who remember the very good reason for the introduction of such legislation in 1956. London was the trigger city. 19th century writers complained that as the city grew and chimneys became more and more numerous, fogs became more frequent, more dense and more over-powering. Condensation nuclei were the cause. Electricity replaced some coal-fired power in the first half of the 20th century but motor traffic made matters worse. On occasions the density of the fog had to be seen to be believed. Yes, I saw it! At times one couldn't see the pavement from the middle of the road. Train drivers couldn't see their signals; traffic was reduced to a crawl or simply stopped. When a temperature inversion was present above the city one could come in from the country on a fine sunny spring day and find that the pall of fog above the city reduced the light over the centre of the city to that of a dull winter afternoon. Building lights blazed everywhere. Condensation nuclei doing their job had taken over the city. The 'final straw' was the smog (the name for the smoky fog) of December 1952 that was considered to be the cause of 10,000 deaths, many immediate, some in the following weeks. The condensation nuclei had gone too far. Inhabitants of many cities suffered from their effects on a lesser scale. Even a modest sized city like Aberdeen with some 200,000 inhabitants and a generous supply of sea breeze could be very unpleasant.

Smokeless zones make cities today pleasant places to breathe in. Coal was the main cause of the problems in the past but no matter how carbon-neutral heating your house with wood stoves is, a lesson our ancestors learnt and which should not be forgotten is that this is not a viable method of heating most houses in a city. Condensation nuclei in big concentrations doing their job can be killers.

Size of nuclei and drops

Smokeless zones haven't eliminated condensation nuclei. They are present due to the natural causes mentioned above and general activity in the biosphere. Typically, in normal air there is a density of 1 condensation nucleus per mm^3, which mightn't sound much but is equivalent to 100,000,000 in the volume occupied by each person (0.1 m^3). Condensation nuclei occur in a wide range of sizes but smaller ones, greater than 0.1 μm, are particularly good for cloud and fog formation. 0.1 μm may sound very small but remember that a single water molecule is about 0.3 nm across and therefore such a condensation nucleus is 300 times its size and over 20 million times the volume of a single water molecule. The condensation particle might just as well be a leaf of grass.

Falling

Tiny particles (of dust) don't fall to the ground at the same rate as heavier particles. Many of the class may remember the falling ball experiment in the first year physics lab and how the table tennis ball accelerated less quickly as it fell compared with other balls. This was because its drag was the same as for other balls of the same size but its weight, which is the downward force pulling it groundward, is less. As we look at particles that are smaller and smaller, we find that the weight reduces as the cube of the dimensions (e.g. 1/10th linear size is only 1 thousandth the weight) but the surface area reduces only as the square of the dimensions, i.e. of 1/10th the size is only one hundredth as small. The ratio of drag force to weight therefore increases and is ten times as much for a particle 1/10th as small. The atmosphere is like syrup for very small particles; they sink very slowly.

A dramatic example of this effect was the ash spewed out from the Eyjafjallajokull volcano in Iceland in April 2010. The ash consisted of very fine glassy particles. If the particles in a kilogram of the ash had been fused together they would have formed a lump that would have sunk like a stone in water, never minding air. In practice they floated high up in the atmosphere where the density of air is less than half its value at ground level, spreading out thousands of kilometres from Iceland over Britain and Europe, grounding all commercial aircraft flights to and from Britain for days, for the first time ever. Major traffic disruption resulted, from glass floating in the sky.

Table 6.1 shows the typical concentration of particles of different sizes in the atmosphere.

As Ahrens points out, not all particles are equally good at holding on to water that reaches them. Some are **hydrophobic**, like the Icelandic ash, and don't let water stick. Good condensation nuclei are **hydrophilic**.

Radiation Fog

The next slides describe how fog forms under different conditions. When air next to the ground is cooled because ground looses heat by radiation on a calm clear night, the air is not stirred up, its base is cold and fog forms close to the ground. This fog can frequently be only a few metres thick and trees stick out of the top. Such fog is particularly found on clear autumn and winter nights.

Valley fog

Cooler moist air drains into the valley. Fog droplets condense as it does so.

Forming Fog

Fog of course forms on condensation nuclei. The greater the source of water, the greater is the chance of fog. Expect it above lochs and wet ground, even above forests or over ploughed fields. Fog droplets do fall to the ground, much faster than condensation nuclei. Any source of water replenishing the fog causes it to persist. A light wind, for example, can bring in more moist air.

Advection Fog

Formed when warm, moist air is blown over a cool surface and wind then brings fog rolling in. The classic example is warm moist air blowing over cool sea, for example, especially sea that is brought by a cool ocean current. This is the cause of the traditional foggy weather in the San Francisco area. It also causes coastal fog that supports a whole local ecosystem in the Namib Desert coastal strip. Here plants have specially evolved to trap droplets that are advected from fog formed above the cold Benguela current that sweeps up the West Coast of South Africa from the cool Southern Oceans.

You don’t need to go to exotic places to experience advection fog. The *haar* that blows in during the summer over Aberdeen and neighbouring coastal regions is well-known here. As a old comforter to children goes in this part of the world: *dinnae fear the haar, bairnie, it’s jist the braith o’ the sea*. Or, as my predecessor many years ago might have said to a student who had done particularly poorly: *yev a haidfil o’ haar, laddie*.

Headland fog is a variant. I know it well for I live beside a headland to the south of Aberdeen. Air coming from the sea in summer is forced to rise by the headland and in doing so cools; it also converges a little as the air on either side of the headland comes together. This convergence increases the density of water vapour and the chance of fog forming.

There are other conditions in which fog forms [*up-slope fog*, *evaporation fog*]. You can read about them.

Clouds

Clouds are described by *appearance* and *height.* Standard names originated with Luke Howard in a paper he delivered in 1802 and subsequently published. They have been used consistently around the world for some 200 years. Luke Howard cracked the problem of categorising clouds sensibly so that you could talk in comparatively few words about changing forms in an ever-changing sky. Cloud forms represent one of the last areas of physical science where Latin based names still have a universal currency.

The key designations for clouds are high (*cirrus*), middle (*alto*) and low (*stratus*).

You should recognise clear occurrences of basic cloud types. There are pictures in the text of the chapter on clouds and a nice cloud chart at the rear of the book. There are also pictures on the web, accessed through the course web page. The following slides illustrate:

- Cirrus (Ci)
- Cirrocumulus (Cc)
- Cirrostratus (Cs)
- Altostratus (As)
- Altocumulus (Ac)
- Stratus (St)
- Nimbostratus (Ns)
- Cumulus (Cu) notice how horizon looks more cloudy
- Cumulonimbus (Cb)
- Other clouds
- Vortex clouds as an example of features seen from satellite

Cumulonimbus (Cb) at hand

The main picture showing greyness in front of the hills may not look special but it is the bottom of a particular cumulonimbus that I remember better than most. I was sailing with my wife in July 2006 on the West Coast of Scotland. We had just passed through the turbulent waters between Lismore Light and Lady Rock light, entering the Sound of Mull. The thumbnail at the bottom right shows the view looking back. With a useful cross-wind, we were making steady progress. However, the atmosphere was unusual. Downwind, on our right, we could see with tremendous clarity right up Loch Lhinne to Ben Nevis and the Lochaber mountains, some 25 – 40 miles distant. Upwind, on our port side, the nearby hills of Mull rising to well over 500 metres were almost hidden in the grey mist you see in the picture. Duart Castle, built on a Mull cliff, is just visible through the mist between the Craignure ferry and the two-masted brig that was sailing alongside us into the Sound. A rain shower seemed inevitable so we donned our oilskins.

Suddenly, or so it seemed, from across the prevailing wind, the rain was upon us, not a shower but a downpour of tropical intensity, accompanied by a squall of gale-force violence. The visibility closed in around us so we could no longer see where we were going. The sails flapped manically; we managed to roll-in much of the foresail but reefing the mainsail was out of the question for lightning flashed close by and then it did so again, a huge zig-zag hitting the sea barely 100 metres away followed by a fearsome crack of thunder less than half a second later. There's no rumble of thunder when you're that close. Within two minutes our peaceful sail had been transformed into the fury of the elements with torrential rain, sail-shaking wind, lightning, thunder and a grey-out into the bargain. "What happens if lightning strikes the mast?" my wife asked. "I don't know and I don't want to find out" I replied, not very reassuringly. I certainly wasn't volunteering to clutch onto our metal mast and reef the mainsail, which is what it takes on our yacht. We steered on by compass-bearing as best we could, peering into the murk fore and aft. We were still in the shipping lane used by Calmac's towering ferries to the Western Isles. Within ten minutes the whole spectacle had passed. Nature's power bundled under a single cumulonimbus cloud. Perhaps I should say "inside a cumulonimbus cloud", for to all intents and purposes we were inside a cloud that reached down to the sea. I was reminded of a useful adage for the outdoor activities enthusiast: *prepare for the worst and hope for the best*. We hadn't, though, been fully prepared for this.

Additional examples of clouds

Luke Howard (1772 – 1864) and historic cloud type pictures

Luke Howard was responsible for naming clouds in a way that captured their essence and that has appealed to people ever since. He first proposed his naming scheme in 1802 and it was published in 1803 under the inconspicuous title of "*On the modifications of clouds"*. Why then? Until the 1780s, clouds were a part of distant and ephemeral nature for almost everyone. Then ballooning took off, literally, and a few people could actually ascend into the clouds and pass right through most of them. Large numbers could watch and even more read about the exploits. Clouds became objects of experience and study. Luke Howard's interest reflected the times and his naming scheme seemed appropriate. By the time the 19th century had closed, Howard's names were the basis of the international system for describing clouds that has been used world-wide ever since.

The intriguing story of how a young self-employed pharmacist came to be naming clouds is well told by Richard Hamblyn in his paperback "*The Invention of Clouds*", which was published by Picador press in 2001. Get hold of a copy if you can. Howard had been fascinated by clouds and skyscapes since he was a young boy sent to a boarding school that had good views over the rolling Oxfordshire countryside. From an early age he was more interested in the natural world outside the class-room and in scientific pursuits than in the study of Latin and other class-room chores but fortunately he had the ability not to fall foul of the schoolmaster by neglecting the work required. As school gave way to the life of an apprentice chemist and, in his 20s, to life as a self-employed shop-keeper and manufacturing pharmacist, he fell in with other young men interested in science and was encouraged to turn his boyhood interests into a subject that he could talk on. You never see the same sky twice, certainly not if there are clouds. How can one make sense of the infinitely variable skyscapes that change not only by the day but by the hour? Howard came up with a scheme that recognised 7 basic cloud types.

His Latin lessons must have made some impact for Howard followed the practice of biology and named his basic cloud forms in Latin. He gave them Latin definitions too. Thus *Nimbus*: "nubes densa, supra patens et cirriformis, infra in pluviam abiens", namely "a dense cloud, spreading out into a crown of cirrus, and passing beneath into a shower", as Howard said after the Latin. He did this at a period when Latin had fallen out of use as the international language of science and there were of course calls for him to give the clouds names in English. The fact that he didn't want to do so was instrumental in the same names being accepted around the world. Had we had a proliferation of names in English, French, German, Spanish, Dutch and a hundred other languages for a nimbus cloud then meteorology as an international discipline would have been impeded. Howard's antiquarian turn of phrase turned out to be a stroke of genius. Now words like *cumulus* don't even seem Latin but have been absorbed into English.

The combination of simplicity and appropriateness allowed Howard's scheme to catch on quickly. Meteorology as a science was in its infancy and Howard provided just the language that was needed. His detailed descriptions were copied in widely read encyclopaedias of the first quarter of the nineteenth century like *Britannica*, *Rees's Cyclopaedia* and the

Encyclopaedia Metropolitana. The new science of meteorology found his names useful. The lecture shows some of the historic illustrations that accompanied these early accounts. In some of these early illustrations the same emphasis is not put on cloud-base height as we now do. Today height is an intrinsic factor distinguishing different types but it was not so significant to Howard. Colour illustrations in books were very scarce in the early days and the final three illustrations show colour prints illustrating three cloud types from my edition of Charles F. Blunt's *The Beauty of the Heavens* published in 1842.

If you like pausing in life from time to time and looking at the sky then look at the web page of the *Cloud Appreciation Society* (http://cloudappreciationsociety.org/), which has over 25,000 members across the world. At the risk of straying from the science in these notes, I'll quote the final verse of Shelley's timeless poem *The Cloud*. It was written in the last year of his life, when he was aged 29. There are 84 lines altogether.

I am the daughter of Earth and Water,
  And the nursling of the Sky;
I pass through the pores of the ocean and shores;
  I change, but I cannot die.
For after the rain when with never a stain
  The pavilion of Heaven is bare,
And the winds and sunbeams with their convex gleams
  Build up the blue dome of air,
I silently laugh at my own cenotaph,
  And out of the caverns of rain,
Like a child from the womb, like a ghost from the tomb,
  I arise and unbuild it again.

Sky Conditions

See the slide:
- Clear < 10% clouds
- Partly cloudy
- Broken clouds
- Overcast > 90%
- Obscured

Cloud cover used to be reported in oktas (1/8th of sky). Looking towards the horizon, any partly cloudy usually looks more cloudy, because we can't see breaks between clouds when looking at an angle to them.

Satellite Observations

The first in any field usually endures a lasting reputation and this is certainly true for the Earth's first artificial satellite – *Sputnik 1*, launched in October 1957. It didn't do much except emit a 'bleep – bleep – bleep' signal for 22 days that let people around the world know it was there but it is given the credit for igniting the space-race that ended up with Armstrong and Aldrin landing on the Moon less than 12 years later. It also announced in effect that 'satellites are go'. The US responded in early 1958 with *Explorer 1*, a satellite in a highly elliptical orbit that discovered the Van Allen radiation belts. It lasted longer than Sputnik since it had the advantage of the comparatively newly invented transistor technology in its electronic circuits but it fell silent after about three-and-a-half months for the same reason as Sputnik, namely its batteries ran out.

Vanguard 2 was planned as the first ‘weather satellite’ with instrumentation to image clouds. It was launched in 1959 but a lack of stability meant it was of little practical use. *Tiros 1* launched the following year was the first successful meteorological satellite, transmitting TV cloud pictures back to Earth. It had solar cells to recharge its batteries and operated for two-and-a-half months. The modern generation of meteorological satellites grew from the succeeding *Nimbus* program that launched *Nimbus 1* in 1964 in a near polar orbit with a range of atmospheric remote-sensing systems.

Britain was the third nation to have a satellite in space, *Ariel 1*, launched from an American rocket in 1962 as part of a program to study the ionosphere. It was also in 1962 that *Telstar* was launched, the first communications satellite that beamed live TV programs across the Atlantic. This had an immediate and wide-ranging social impact, for never before had live coverage of TV been available at such a distance since transatlantic telephone cables didn’t have the bandwidth to transit TV signals. Telstar used energy guzzling valve technology but it was covered with solar cells and like Ariel would have lasted longer than the few months it did had not they both been incapacitated by a high-altitude nuclear test. Such were the times in 1962.

Communications satellites became the first geostationary satellites, orbiting at a more or less fixed point above the equator at an altitude of just under 36,000 km. *Syncom 2* was the first successful one, launched in 1963. In spite of the social impact of Telstar, rocket technology was seen in Europe as basically part of military technology and why should Britain and other western European countries spend money on duplicating what the Americans were doing? Europe was slow in seeing the civilian use of satellites. The British rocket program, which launched the British satellite *Prospero* in 1971, was cancelled in that year. European effort did regroup in the 70s and Europe launched its first, prototype, meteorological satellite, *Meteosat 1*, in 1977 and the next one in 1981, some 2 decades behind the Americans. Meteosat was a geostationary satellite.

We take ‘weather satellites’ and communications satellites for granted these days but it took several decades before they reached today’s level of sophistication. See the slide for the two types of satellite orbits and some of their characteristics.

Geostationary Conditions

Geostationary satellites are located about 36,000 km above the Earth’s *surface* (42,200 km from centre of the Earth). A geostationary satellite orbits the centre of the Earth once in 23 hours 56 minutes 4.09 seconds and hence stays above the same place. Satellites and their orbits obey Kepler’s laws of orbiting bodies. Satellites are all in *planar orbits* about the *centre of Earth*, i.e. the plane of the orbit must pass through the centre of the Earth. [The centre of the Earth is the point where all gravitational attraction is directed towards]. A satellite orbiting in any plane at the right height will go around once in the 23 hours etc. mentioned above but it will only stay above a fixed location on the Earth if its orbital plane includes the equator. Hence geostationary satellites are all above the equator and they always look down obliquely on Europe. In other orbital planes a satellite will track across a path that circles the Earth.

Polar orbiting satellites

E.g. the NOAA series [National Oceanic and Atmospheric Administration], scan the whole Earth. They have typical orbital times of around 100 min and a much lower altitude than geostationary satellites, typically 900 km. They do not go directly over the Poles but are in orbits tilted about 8° away from a true polar orbit. They are sun-synchronous, slowly rotating their orbital planes in a year to keep passing over a particular area at similar times of the day in different months.

More on Geostationary Satellites

They have a fixed view - successive frames can make a video, several sensors produce pictures in the visible and IR - not TV cameras but scanning instruments; range of wavelength channels (multispectral). American GOES (Geostationary Operational Environmental Satellite) do more than just image clouds - see Ahrens.

Coverage of geostationary meteorological satellites

Coverage maps, courtesy Dundee University receiving station.

Polar Orbiting

These look almost straight down - more detail is seen because they are some 40 times closer than geostationary satellites. Perhaps ‘straight down’ is not a very accurate description. They obviously look sideways too. If you stand on the top of a conspicuous hill then you know that when you look down the hill you see the fine details of the ground below but when you look a lot to the side you see much further away but the landscape is foreshortened. ‘Low Earth Orbit’ (LEO) meteorological satellites look down from typically 900 km up. How much can they see? If they scanned 45º on either side of straight down then a quick sketch will tell you that they see a scan of about 1800 km wide. When a satellite comes around again some 100 minutes later, will the region it now sees overlap with the region it saw previously, given that the Earth has turned round on its axis 25º in 100 minutes? Near the poles there will be no problem in securing overlap. However, at the equator there is about 2800 km between lines of longitude 25º apart so this polar orbiting satellite will necessarily leave a gap of some 1000 km between successive scans. For an actual satellite the width of the gap and at which latitude it begins depends on just how widely it scans, its height and the fact that real polar orbiting satellites don’t go exactly over the poles but have an orbit inclined to the equator at nearer 80º than 90º. You will see the gaps, though, where there is a single satellite involved in monitoring such variables as ozone density, sea-level winds and so on.

Today's cloud pictures are available from Dundee University. Ahrens explains that IR images show brightest from the hottest bodies. The pictures, though, are grey-scale coded so that coolest clouds (and therefore the highest) appear white while warmer, lower, clouds appear dark grey. IR images at night are recorded from the IR emitted by all bodies (remember peak of black-body radiation at 300 K is at a wavelength of 10 μ).

Satellite Images - not in textbook

1. Hurricane Hugo

2. Comparison of IR and water vapour images from meteosat
3. Enhanced geostationary sat image
4. Example of composite image - full hemisphere on Mollwiede projection
5. Wisconsin’s composite cloud/temperature image
6. Antarctica
7. Recent picture of cloudless Britain
8. Average North Sea temperatures over 4 years in July. Confirmation that Aberdeen’s sea is really cold!

JSR