INTRODUCTION TO CLOUDS

- Clouds are very common, with 50% of Earth covered in cloud at any one time.
- Only 1 – 2% will be raining.
- They are classified by height and nature:
  - Low clouds: base 0 – 2 km
  - Medium clouds: base 2 – 7 km
  - High clouds: base above 5 km

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Over Planet Earth as a whole, rain is the most common type of precipitation. Other common types are snow, sleet and hail.

Clouds are classified into ten main types depending on height and nature – as we see later in this talk. Clouds composed of ice crystals are, by definition, high clouds. The height ranges given on the slide are for middle latitudes. The figures for low latitudes are, respectively, 0-2km, 2-8km and 6-18km. The figures for high latitudes are 0-2km, 2-4km and 3-8km.

WHAT ARE CLOUDS MADE OF?

- Most clouds are made up of vast numbers of water droplets, each droplet about a hundredth of a millimetre (10µm) in diameter.
- Typically, about 100 droplets in each cubic centimetre of cloud.
- High clouds composed of ice crystals, in a variety of shapes and each about 100 µm long.
- Typically about ten ice crystals in every cubic centimetre of cloud.
- … and supercooling occurs …

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Clouds are very heavy. A cubic metre of water weighs a tonne and some clouds weigh many tonnes. Clouds do not fall, however, because they are held aloft by the rising air which is responsible for their formation.

SUPERCOOLING

- Water can exist in the atmosphere at temperatures well below 0°C, a condition known as ‘supercooling’.
- Even at temperatures below -30°C, clouds may contain supercooled water droplets.
- Medium-level clouds are composed mainly of supercooled water droplets.
- High clouds composed entirely of ice crystals.

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The existence of water in the atmosphere at temperatures below 0°C is known as supercooling.

For supercooling to exist, atmospheric motions must not be too vigorous, but even near the ground, where the atmosphere is quite turbulent, supercooling is not uncommon. Fog containing supercooled water droplets can occur, for example, but the droplets freeze on impact when people walk through the fog or drive through it. Vertical motions are quite slow in most medium-level clouds - typically 5-15cm/s.

Supercooled water cannot exist in contact with ice. The water then freezes immediately.

The main types of cloud are:

- Cumulus (cauliflower appearance)
- Stratus (flat, grey and dull)
- Cirrus (wispy mares’ tails)

If a cloud produces rain then the prefix *nimbo-* is added or the suffix *-nimbus* appended (from *nimbus* = rainy cloud), e.g. nimbostratus, cumulonimbus.

Medium-level clouds have the prefix *alto-*, e.g. altocumulus, altostratus.

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Latin words are used for naming clouds.

Cumulus means ‘heap’ or ‘pile’ or ‘mass’; and cumulus clouds, particularly the taller ones, often look like large cauliflowers.

Stratus is the past participle of sternere (from sterno) and means ‘strewn’ or ‘spread’. Stratus clouds take the form of horizontal sheets or layers.

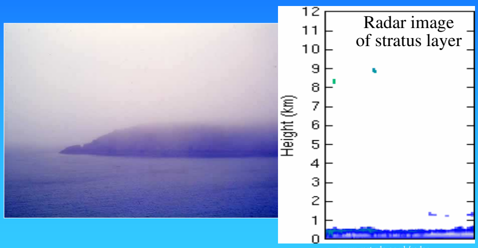
Cirrus means a ‘lock’ or ‘curl’ of hair; and cirrus clouds are generally fibrous or hair-like.

Nimbus means ‘rainy cloud’; and clouds containing the prefix *nimbo-* or the suffix *–nimbus* produce precipitation (i.e. rain, snow, sleet, hail, etc).

Alto- derives from alo and alere and means ‘high’.

The most hazardous type of cloud is cumulonimbus, as we see later in this talk.

STRATUS: low-level cloud



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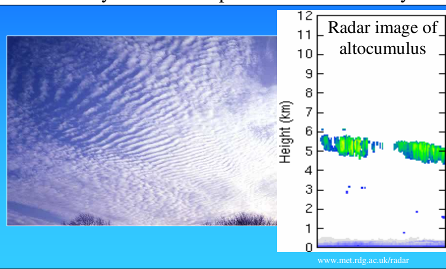
The radar picture on the right comes from the Chilbolton radar facility in Hampshire, UK.

The radar sends out a beam which is reflected by water and ice (and insects!). The colour represents the strength of the beam that is reflected. The larger the water droplet or ice the stronger the reflected beam, with strong reflections displayed red and weaker reflections blue.

Note how low the stratus is. The radar shows it to be only 4-500 m deep. Therefore, if you were able to get above the cloud it would be a lovely sunny day. You could try this by going up a mountain. However, you need to make sure that topographical cloud is not being formed by the mountain itself! If there is low-level stratus present and we have a high pressure system, the stratus cloud will be found below the anticyclone's inversion.

As stratus cloud is so shallow, only drizzle is able to form. Indeed most of the time there is no precipitation - just a dull grey blanket, consisting only of water droplets.

ALTOCUMULUS:
medium-level cloud
made mostly of water droplets with some ice crystals



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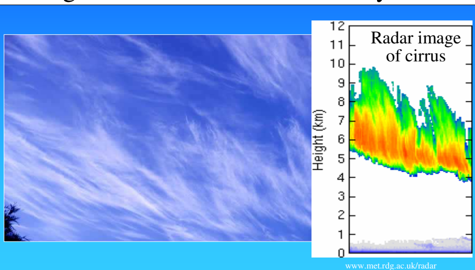
Altocumulus clouds occur at medium levels in the troposphere in the form of sheets or layers of cloud which are broken up into masses, rolls or cells. The breaking up results from a range of processes, as we see later in this talk (see altocumulus lenticularis and altocumulus castellanus). The rippled appearance of the clouds on this slide resulted from wind shear, with the wind at the top of the cloud being stronger than the wind at the bottom.

Altocumulus clouds are made up of water droplets and ice crystals. When temperatures are below zero degrees Celsius at altocumulus levels, as they often are over the British Isles, the water droplets are supercooled.

Altocumulus can easily be confused with cirrocumulus and stratocumulus. The elements of altocumulus are generally larger than those of cirrocumulus and smaller than those of stratocumulus. Cirrocumulus clouds show no shading. Altocumulus clouds are medium-level clouds, whereas cirrocumulus clouds occur in the upper troposphere and stratocumulus clouds in the lower troposphere.

CIRRUS:
high-level cloud made of ice crystals



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This cloud has a fibrous hair-like appearance and is made of ice crystals.

The radar image shows the cloud to be quite deep, though to us cirrus cloud often appears thin. This is because the ice crystals are present at depths from 4 to almost 10km (in this radar shot at least) and reflect the radar's beam particularly well. The crystals tend to be quite spread out so if you were looking at this cloud it is likely that you would also be able to see blue sky through the cloud.

HOW DO CLOUDS FORM?

- When a parcel of air rises, it expands and cools.
- The ascent is adiabatic (i.e. no heat leaves or enters the rising parcel).
- Ascending unsaturated air cools at 9.8ºC per km.
- If it cools sufficiently, water vapour condenses onto particles in the atmosphere to form cloud.
- These particles are known as condensation nuclei.

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Air contains water vapour; and its capacity to hold vapour decreases with temperature. When a parcel of air rises, it expands and cools adiabatically. Eventually, the air becomes saturated, i.e. its vapour pressure is then the same as its saturation vapour pressure at that temperature. Further ascent leads to condensation, i.e. the formation of liquid water. If the temperature is below zero degrees Celsius, supercooled water droplets generally form, unless the temperature is too low for this to happen, in which case the water droplets freeze immediately to become ice crystals.

Ascending unsaturated air (i.e air that does not contain cloud) cools at 9.8ºC per km. Once cloud has begun to form, latent heat of condensation is released inside the rising parcel of air, as a result of which the ascending air cools at less than 9.8ºC per km (generally between 4 and 7ºC per km).

For a cloud droplet to form, there must be condensation nuclei present. These are tiny particles in the air, e.g. sea salt or dust. Fortunately, there are plenty in the air (1000 per cc over cities). The water vapour will condense onto the nuclei to form droplets. Therefore, no water droplets are ever made up of only pure water but will have impurities present.

The three main processes which cause air to rise are as follows:

- Lifting at an air-mass boundary (frontal uplift)
- Convection (when air is heated from below)
- Orographic uplift (air forced upwards over mountains), in which case there are two possibilities:
  - When air is stable, lee waves form over the mountains and downwind of them
  - When air is unstable, cumulus or cumulonimbus clouds form over the mountains

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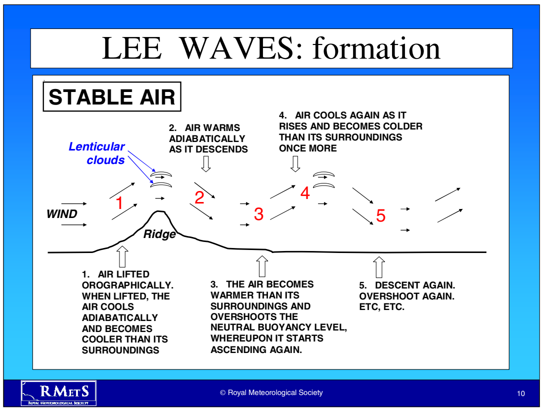
FRONTAL UPLIFT: Fronts are boundaries between air masses of different temperature and humidity. When these masses meet, they do not readily mix. Instead, they tend to remain separate, with the cooler, more-dense mass undercutting the warmer and less-dense mass. Thus, there is upward movement of the warmer air mass.

CONVECTION: When the sun heats the ground, the air next to it will in turn be heated. The warmer air is less dense than the air above it and therefore rises - in large bubbles known as thermals. Convection also occurs over the sea where cool air is warmed by passage over a warmer sea-surface, as is the case on the western flanks of the mid-latitude depressions that cross the British Isles.

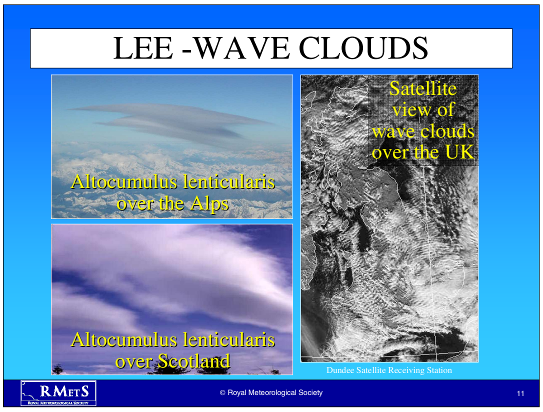
OROGRAPHIC UPLIFT: The forced ascent of air over a topographic barrier such as a hill or mountain is called orographic uplift. In such circumstances, the ascending air may be stable or unstable. We consider these two stability cases in the next few slides.



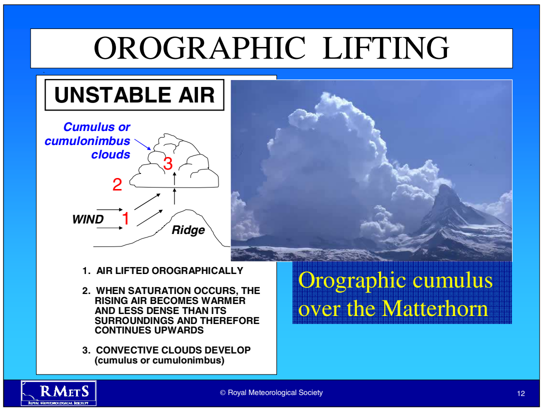
Let us first consider the case of the atmosphere being stable.

When stable air encounters a hill or mountain, it tries to go round, but if this is not possible the air is lifted and becomes cooler than its environment (i.e. its surroundings). This happens because the lapse rate in the environment (called the environmental lapse rate) is less than the lapse rate in the rising air (the dry-adiabatic lapse rate). Once cooler than its environment, the air decelerates upwards and then starts to descend, whereupon it warms adiabatically and becomes warmer than its environment. It overshoots the level of neutral buoyancy and thus begins to ascend again, again cooling as it rises and becoming cooler than its environment. Descent then occurs again; and the process continues downwind for some distance.

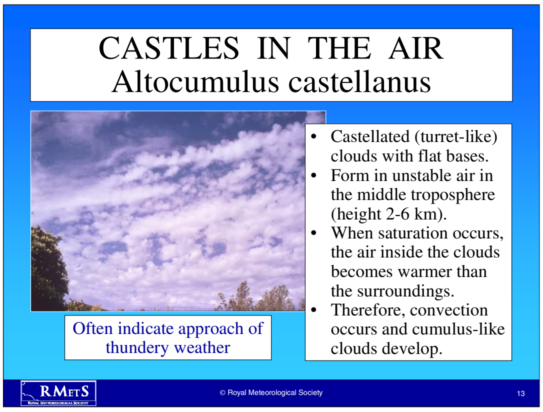
When the atmosphere is moist enough, lenticular (lens-like) clouds form in the ascending air. These are usually at medium levels, in which case they are called altocumulus lenticularis, but they may occur in stratocumulus or high clouds. Lenticular clouds can sometimes be seen 300km or more downwind of mountains.



On the slide, the satellite view of lenticular clouds over the UK shows the characteristic pattern of parallel cloud bands downwind of hills and mountains, with the bands at right-angles to the wind.

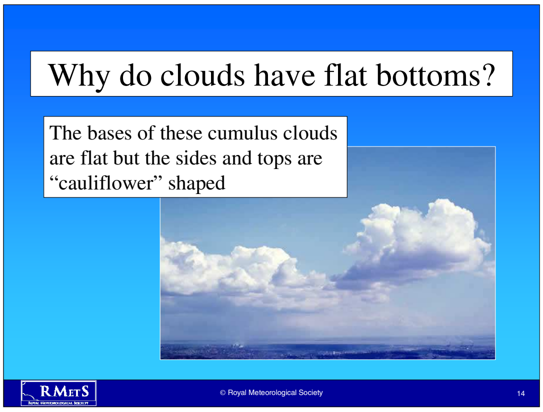


When unstable air encounters a hill or mountain and is lifted, it becomes warmer and less dense than its surroundings, because the environmental lapse rate is greater than the dry-adiabatic lapse rate. The air therefore continues upwards. If the air is moist enough, cloud forms – and this cloud is convective in nature, i.e. cumulus or cumulonimbus. If the depth of the unstable air is limited, as in the picture on the slide, cumulus cloud forms. If the unstable layer is deep, cumulonimbus clouds develop.



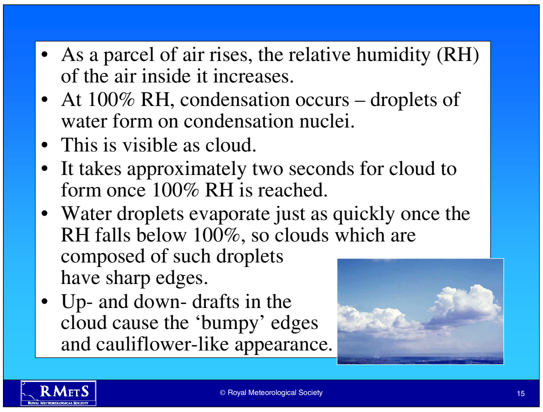
Sometimes, altocumulus clouds have a castellated appearance, i.e. their upper parts look like castle turrets. These turrets are, in fact, small cumulus clouds growing from the altocumulus and their appearance shows that the atmosphere is unstable at medium levels. When the altocumulus forms, the latent heat which is then released causes convection to occur. Sometimes, the turrets become tall enough for precipitation to form; and when this happens, trails or streaks of precipitation (called *virga*) may be seen below the cloud. Normally, the precipitation soon evaporates, but it may occasionally reach the ground.

The appearance of altocumulus castellanus often indicates the approach of thundery weather.



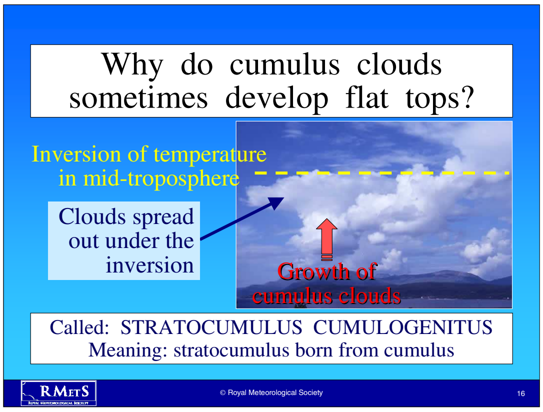
This aspect of clouds is best seen when fair-weather cumulus clouds are present. As the sides and tops are bumpy, why aren’t the bottoms?

An explanation is given on the next slide.



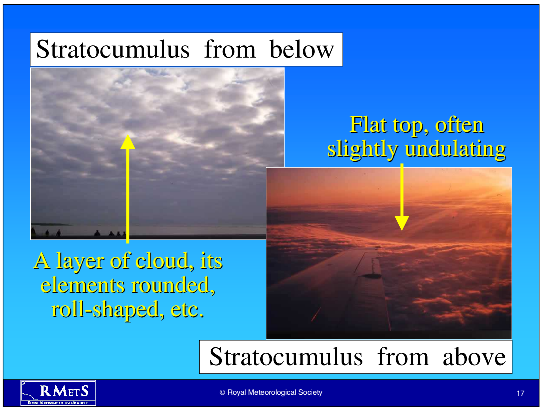
Cumulus clouds develop in an unstable atmosphere. Beneath the clouds, there are rising bubbles of buoyant air, with the air in them typically rising at 1-5m/s. At the condensation level, saturation occurs, and this is shown by the flat bases of the clouds. Further ascent of the bubbles causes the formation of clouds with upper parts like cauliflowers.

At the edges of the clouds, there is mixing with unsaturated surrounding air, and evaporation of the water droplets on the edges thus occurs. The edges therefore cool, because of latent heat absorption, and the clouds develop thin skins of cool air which sink fountain-like.



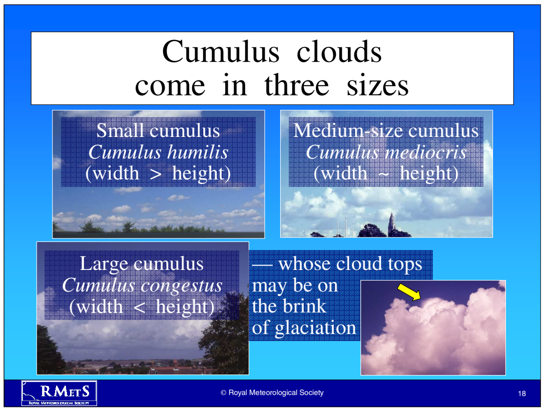
The vertical growth of cumulus clouds can be limited by a stable layer. The buoyant bubbles of the clouds do not penetrate the inversion but spread sideways to form an area of stratocumulus cloud which is called stratocumulus cumulogenitus, meaning “stratocumulus born from cumulus”.

This often happens in hilly parts of the British Isles on a day which starts clear and sunny. Not uncommonly, cumulus clouds begin to develop during the morning and after a while spread, so that a layer of stratocumulus cloud has formed by mid-late morning.



From below, stratocumulus clouds appear as grey or whitish sheets in which there are tessellations, rounded masses, rolls, etc. The sheets are shallow – often no more than about 1,000m deep. Above them, the air may be cloudless.

Waves occur at boundaries between fluids of different density where the lower fluid is more dense than the one overlying it. Thus, waves occur on water surfaces, where the density of the water is considerably greater than the density of the overlying air. They also occur along inversions in the atmosphere, as the right-hand picture shows. Here, there is a change in density at the inversion, with the air above the inversion less dense than the air below. The waves themselves may originate as lee waves.



Meteorologists distinguish three types of cumulus cloud:

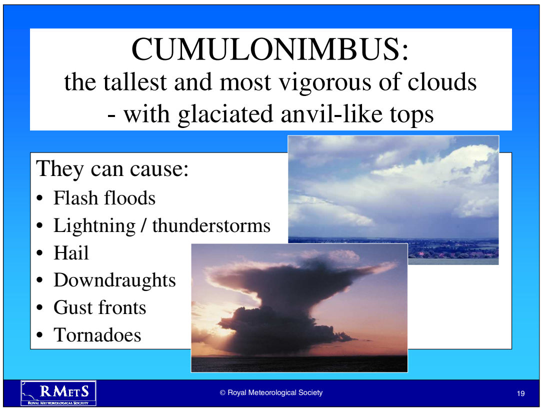
Those of small vertical extent are called *cumulus humilis* (humilis = low).

Those of moderate vertical extent are called *cumulus mediocris* (mediocris = medium).

Those of considerable vertical extent but not yet producing precipitation are called *cumulus congestus* (congestus = piled up).

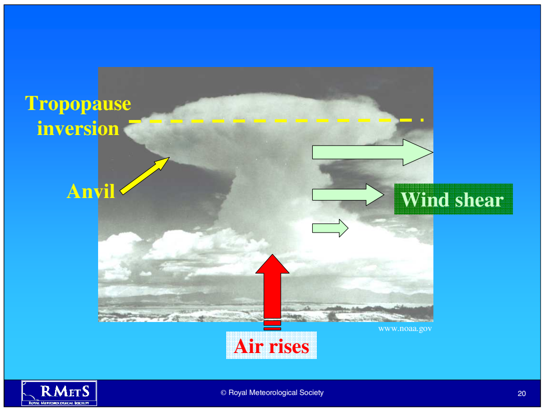
Cumulus-type clouds which produce precipitation are called *cumulonimbus*.

The vertical extent of cumulus growth is governed by atmospheric stability. The deeper the unstable layer, the taller the clouds.



The tallest clouds of the cumulus type are called *cumulonimbus*. They are towering clouds which produce precipitation. Their upper parts are composed of ice crystals and are often anvil-shaped, this shape resulting from the vertical growth of clouds being limited by the tropopause. The ascending air cannot penetrate the inversion and instead spreads sideways. The tops of cumulonimbus clouds are glaciated because temperatures are too low in the upper troposphere for supercooled water droplets to exist.

Cumulonimbus clouds can cause flash floods, thunderstorms, hail, downdraughts, gust fronts and tornadoes. Thunderstorms seldom consist of single cumulonimbus clouds. They generally contain several clouds in different stages of development or decay. Cumulonimbus clouds can produce heavy rain; and if a group of these clouds becomes slow-moving or even stationary over a comparatively small area, amounts of rain over the area may be so great that flash flooding occurs. Flying through cumulonimbus clouds can be very dangerous because there are strong up-currents and downdraughts inside the clouds. Very gusty conditions often occur beneath cumulonimbus clouds; and in some cumulonimbus clouds - notoriously in the US Mid-West in spring and summer - tornadoes may develop.



This slide shows the mature stage of a severe thunderstorm. Release of latent heat in the ascending humid air provides the power for the storm cloud. The tropopause inversion has the effect of capping the rising air, but the speed of ascent of the air inside the cloud can be so great that some over-shooting through the inversion can occur.

The anvil head forms when the ascending air reaches the stratosphere (approximately 8 – 12 km high). Air above the tropopause inversion is stably stratified and inhibits any significant further vertical ascent as air parcels meet resistance if they try to rise higher.

If the wind is constant with height, the falling rain and sinking cold air counteract the rising warm air and thus cause the storm to dissipate.

If, however, there is a strong wind shear, meaning that winds aloft are significantly stronger than low-level winds, a severe storm can develop. In such storms, the rising air becomes separated from the falling rain and sinking cold air and the environmental conditions required for development thus become enhanced.

POLAR STRATOSPHERIC CLOUDS

- Iridescent ('mother of pearl').
- Very high cloud (~15-25 km).
- Very low temperatures (-75° to -95°C).
- In high latitudes in winter (Alaska, Scandinavia, Scotland, Antarctica).
- Nacreous clouds.
- Frozen water droplets and nitric acid hydrates.
- Probably important in respect of the so-called 'ozone hole'.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These are rare clouds and have the appearance of mother-of-pearl. They occur mostly but not exclusively in high latitudes and form high up in the atmosphere – typically 15-25km. They are wave clouds found downwind of hilly regions and mountain ranges. They form at very low temperatures (minus 75 to minus 95°C) and are mostly composed of ice particles about 10µm across. Those which form naturally in unpolluted air are called nacreous clouds.

Today, many polar stratospheric clouds are composed not just of ice particles but also crystalline nitric acid hydrates and other chemicals. Especially important nowadays are the chlorofluorocarbons (CFCs) which are very long-lived and reach the stratosphere. Chemical reactions on the surfaces of the particles of polar stratospheric clouds are believed to be of major importance in causing ozone depletion, especially in the extremely cold air of the polar vortex in the southern hemisphere.

MAN-MADE CLOUDS

- Condensation trails ('contrails') behind aircraft.
- Exhaust gases cool rapidly, mainly because of mixing of these hot, moist gases with their surroundings.
- Contrails made of ice crystals, and some, in fact, can spread sufficiently to form extensive patches of cirrus.
- Contrails and contrail-related cirrus among the important impacts of aviation on climate.

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Contrails can regularly be seen in the UK. They are trails of ice crystals left in the wakes of jet aircraft. They are condensation trails (known as 'contrails') and sometimes persist for many minutes or even hours. On other occasions, they disappear quite quickly.

The exhausts of aircraft engines are hot and moist, the water vapour in them coming mostly from combustion of hydrogen in the aircraft's fuel. Behind an aircraft, exhaust gases cool rapidly, mainly from mixing with their surroundings but also to a small extent as a result of radiation loss. This cooling takes a finite time (a fraction of a second), so there is normally a gap of some 50 to 100 m behind an aircraft before a contrail appears. The water droplets that are produced freeze very rapidly if the temperature is low enough. The resulting trails of ice crystals persist and spread if the atmosphere at contrail level is moist enough. Contrails (and water droplets) form when the saturation vapour pressure ***with respect to liquid water*** is exceeded. They persist when the air is saturated or supersaturated ***with respect to ice***.

Once formed, contrails are distorted by upper winds and spread by diffusion, and curtains of ice crystals can sometimes be seen falling from them. Persistent trails often form large patches of fibrous clouds that look like cirrus, cirrocumulus or cirrostratus. Thus, old contrails sometimes cannot be distinguished from these clouds.

Clouds composed of water droplets can persist at temperatures well below 0°C, even at temperatures below –30°C. At temperatures below about –40°C, however, all cloud droplets freeze very quickly. On long-haul routes, commercial aircraft usually reach altitudes of 10 to 12 km, where temperatures are typically below –40°C. Planes on these routes therefore tend to leave contrails behind them. Over the British Isles, trails rarely form below about 8 km in summer, 6 km in winter. When the weather is as cold as it often is in mid-winter in Alaska, Siberia and central Canada, contrails can even form at ground level. Indeed, airfields in these regions have sometimes had to be closed when low-level clouds (ice fogs) composed of aircraft-generated ice crystals have proved persistent.

The rapid reduction in pressure that occurs immediately behind an aircraft causes condensation trails to be produced adiabatically at wing surfaces and, particularly, wing-tips. Such trails often have a wavy appearance, consistent with the occurrence of complex vortices (twisting rotating eddies) behind the aircraft.

Contrails used to be used by the military to assess the height of aircraft; also avoiding regions of the atmosphere where conditions were right to make contrails meant that there was much less chance of being spotted by those on the ground, therefore giving a tactical advantage in warfare.

PREDICTING CLOUDS

- Very important to predict them accurately
- Clouds reflect solar and long-wave radiation
- Low cloud acts to cool Earth's surface during the day and warm it during the night
- Warmer climate = more cloud ?
- Could Earth self-regulate its temperature?

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Although the mechanisms for cloud formation are well known, the presence of cloud is difficult to predict. This is important not just for our daily TV forecast but also for climate change.

Convective clouds can form, produce rain and dissipate in as short a time as 30-90 minutes. They are of relatively small size (a few kilometres high and wide) but the numerical weather model uses a grid of 40km square so it is not possible (yet) to predict such small clouds. Larger cloud systems, e.g. cloud along a weather front, may extend over hundreds of kilometres so can be better predicted.

The presence (or absence) of cloud is extremely important for climate prediction and even our best models cannot predict it well. It is sometimes argued that if Earth's climate warms then this will result in more cloud. Thick low-level cloud tends to reflect solar radiation back to space, so an increase in low cloud would tend to cool climate. On the other hand, high-level cloud tends to trap long-wave radiation and prevent it reaching space; an increase in high cloud might lead to Earth heating up even more! The presence of more cloud could mean that the Earth self-regulates its climate. There is, currently, little agreement on future changes in cloud cover.

SUMMARY

- Clouds are very common.
- They are classified by height and shape.
- They are caused by water vapour condensing onto condensation nuclei.
- They can cause severe weather hazards.
- They are very difficult to predict.

Talks in a Box

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