

# Clouds

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## Abstract

In this article we aim to give an introduction to clouds; what they are, why they matter and how the physical processes operating in the atmosphere govern the appearance and behaviour of the clouds we see.

## Introduction

Clouds are the most visual interaction that we have with the atmosphere and meteorology. They can be indicative of fine weather, such as fair-weather cumulus; they are harbingers of powerful and potentially destructive atmospheric conditions in the case of cumulonimbus; and they can also be enigmatic and beautiful, like mammatus or Kelvin–Helmholtz instabilities. All of these types of cloud will be covered in this article but, more generally, the aim is to give a brief overview of why clouds are important, how clouds form and show some examples of different types of cloud.

First of all, though, a simple question: what are clouds? The similarly simple answer is that clouds are water droplets (or sometimes ice crystals)—up to  $10^{12} \text{ m}^{-3}$ , typically about 0.02 mm in diameter—but water, nonetheless. These droplets have the effect of scattering light, which, in turn, makes them visible and appear milky coloured. It is also important to note that clouds are generally only present in the lowest region of the atmosphere known as the troposphere, which reaches up to around 10 km in the mid-latitudes, in which temperature falls with height (figure 1) and in which vertical motion is common.

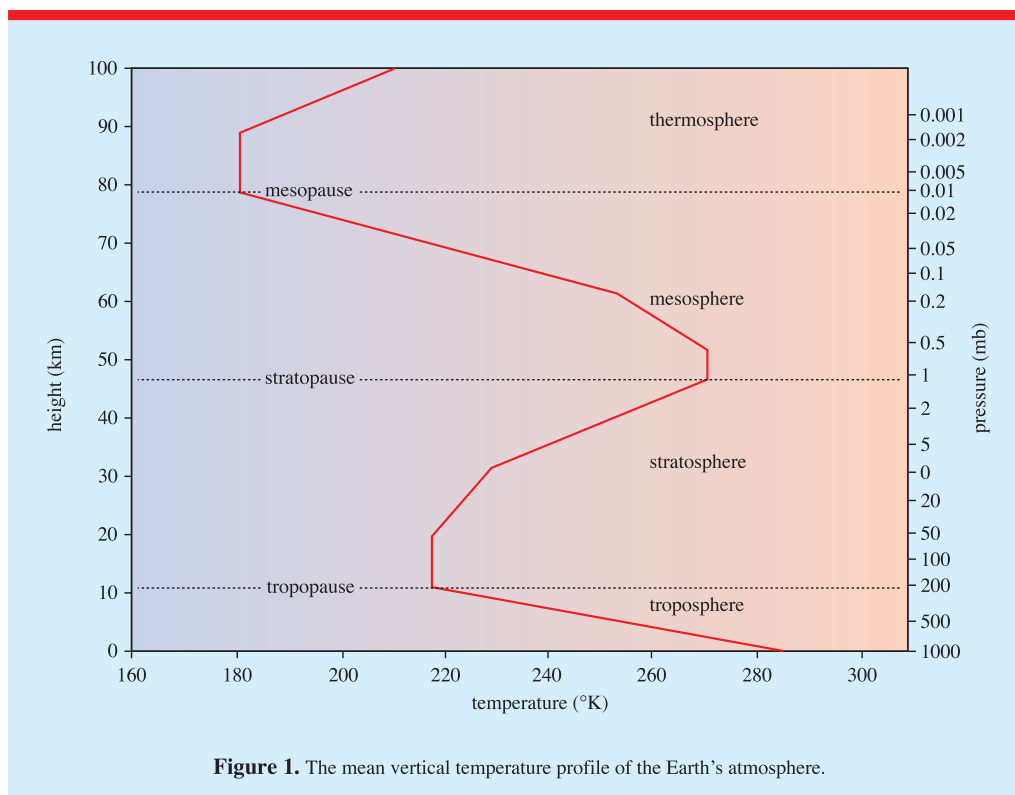
## The importance of clouds

The water cycle is essential to life on Earth. It is therefore important to understand the mechanisms by which this cycle is driven, especially the locations where, and methods by which, clouds

and precipitation form. It is equally valuable to know how this cycle may change in the future. Clouds are also responsible for the removal of certain pollutants from the atmosphere. Finally, clouds play an important, albeit complicated role, in the climate system. Different types of cloud have different effects on the climate. For example, some clouds are bright white and reflect a lot of the incoming solar radiation—they have a high ‘albedo’—thus having a cooling effect. However, water vapour is also a very powerful greenhouse gas and so, in a warmer climate with subsequent increases in evaporation from the ocean, an increase in cloud cover would have a compounding warming effect—a so-called ‘positive feedback’ of climate change. Despite the importance of climate feedback, they were notable by their absence in the research discussed by the recent, and very cautious, 2007 Intergovernmental Panel on Climate Change (IPCC) report on climate science. Further to this dichotomy of cloud–climate effects, the representation of the amount and different types of cloud in climate models (box 1) is not particularly good. All in all, the study of clouds is not a fluffy matter.

## Condensation

Clouds form via the condensation of water vapour, the fundamental idea being that water vapour condenses more readily out of cold air than out of warm air. The reason for this relationship is that the equilibrium point of the concentrations of vapour and liquid is linked to the energy required



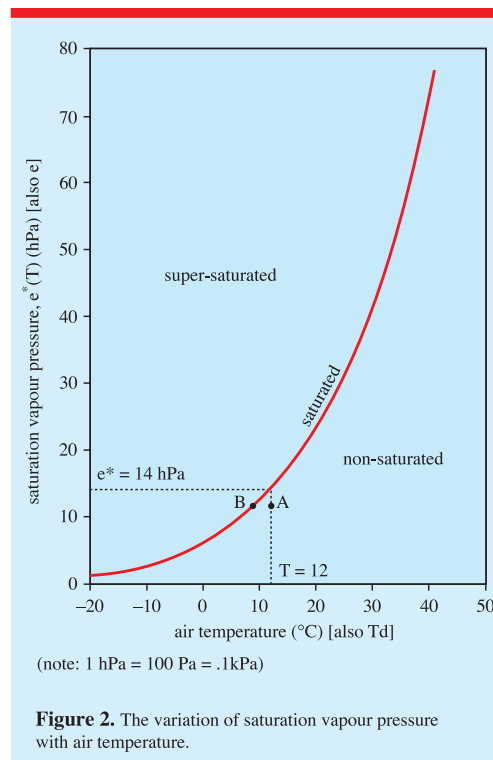
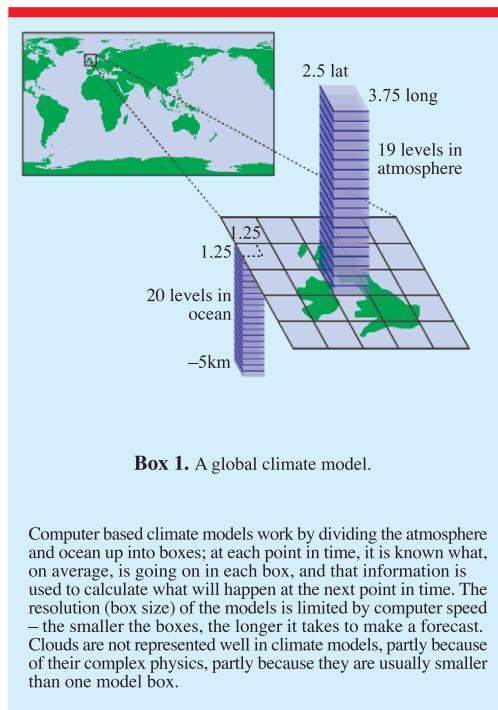
**Figure 1.** The mean vertical temperature profile of the Earth's atmosphere.

for the phase change, which is itself linked to the temperature. This relationship is usually expressed in terms of vapour pressure, which is the partial pressure exerted by water vapour. To give two examples, think of what happens when warm moist air from your shower hits a cold mirror or when the moisture in your breath becomes visible on a cold day. In the atmosphere the same process is at work: when a parcel of relatively warm moist air cools for one reason or another (the typical mechanisms for which will be covered later) the air becomes saturated, the water vapour can condense, and a cloud can form. The point at which this happens is known as the 'dew-point temperature' or the 'saturation vapour pressure' (figure 2).

However, reaching the saturation point is not sufficient for condensation to occur. Indeed, droplets will not form spontaneously until the air parcel reaches very low temperatures, often below 0°C. At this point the vapour is termed 'supercooled'. As an example, imagine a pint of lager or a sparkling soft drink (if you are driving). Although these drinks are supersaturated

with carbon dioxide (CO<sub>2</sub>) all of the gas does not escape spontaneously when the seal of the can or bottle is broken and the drink is poured. If you look closely, you can see that bubbles do not form at random sites: they form at places where there are imperfections or (in a poor-quality drinking establishment) dirt on the surface of the glass. Points where the CO<sub>2</sub> changes phase (or nucleates) and escapes from the beer are called nucleation sites. Adding salt to the drink increases the number of nucleation sites and produces noticeably more bubbles (small glass beads can be used instead to show that the release of CO<sub>2</sub> is not due to a chemical reaction with the salt). In effect, this creates a 'reverse cloud' in the beer, in the sense that there is a cloud of CO<sub>2</sub> gas in the main body of liquid. This experiment is explained in more detail by Bohren (1987) in his book *Clouds in a Glass of Beer: Simple Experiments in Atmospheric Physics*.

Returning to the atmosphere, these ideas can be used to show that water droplets are similarly much more likely to form when there



are very small particles present onto which the vapour can nucleate. As nucleation starts and the droplet grows, more vapour can then join the initial seed and the droplet grows further—a process called coalescence. Typical particles in the atmosphere (termed aerosols) that act as cloud condensation nuclei, or CCN, are dust, soot, sea salt, phytoplankton or sulfate and are usually of the order of 0.0001 mm in diameter. In this way, pollutants in the atmosphere are incorporated into clouds and can subsequently be rained out of the atmosphere.

### Cloud types

In discussing the so-called ‘cloud genera’ it helps to have translations of the commonly used Latin terms. Here are some for starters:

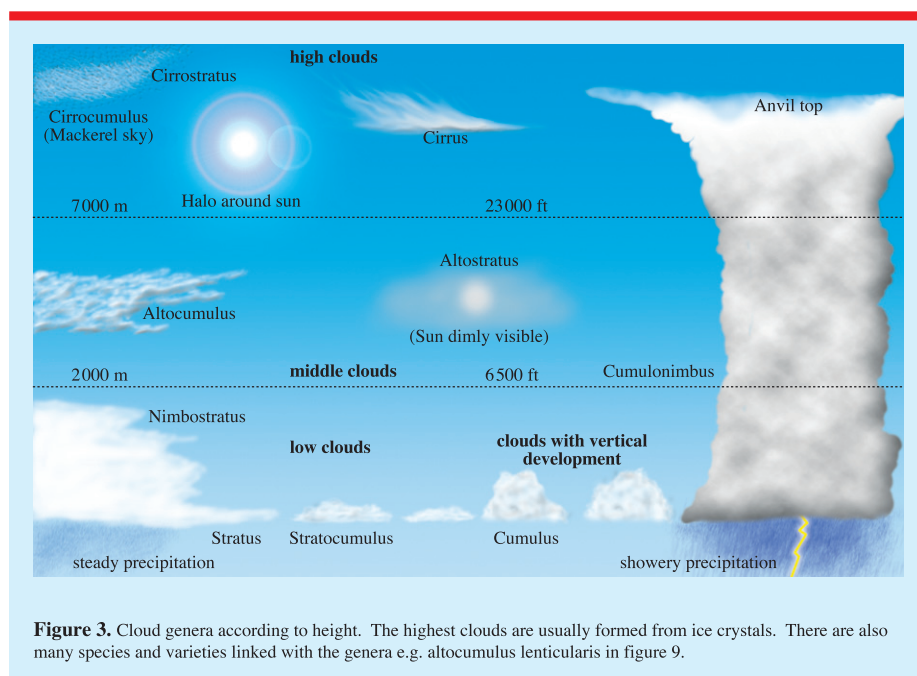
- cumulus means heap or fluffy;
- stratus means layer or sheet;
- nimbus means ‘rain cloud’;
- cirrus means fibre or ‘lock of hair’;
- alto means ‘high’ (although, rather unhelpfully, it refers to mid-tropospheric cloud).

Translations of many of the other names (with picture examples) can be seen in the Karlsruhe Cloud Atlas (see <http://tinyurl.com/28tg32>) that is itself based on the comprehensive World Meteorological Organisation’s ‘Cloud Atlas’ publication. However, it makes sense to discuss these most common types of cloud alongside their typical methods of formation, as will be done in the following sections.

### Cloud formation

As mentioned in passing in a previous section, clouds form ‘when a parcel of relatively warm moist air cools for one reason or another’. In the atmosphere, this cooling generally occurs when parcels of air ascend to regions of lower pressure. If the quite reasonable assumption that there is no heat added to or extracted from the gas in this process (i.e. it is adiabatic) is made, then it is relatively easy to get from the ideal gas law ( $pV = nRT$ ) and the first law of thermodynamics ( $dq = du + dw$ ) to Poisson’s equation:

$$(T/T_0) = (p/p_0)^k$$



**Figure 3.** Cloud genera according to height. The highest clouds are usually formed from ice crystals. There are also many species and varieties linked with the genera e.g. altocumulus lenticularis in figure 9.

where  $k = 0.286$ . This equation describes the change in temperature of an air parcel with changes in pressure. A complete derivation of Poisson's equation can be found in many meteorological textbooks but, in particular, it is the starting point in Rogers and Yau's excellent text *A Short Course in Cloud Physics* (Rogers and Yau 1996).

If the parcel cools sufficiently and there are particles for the vapour to condense onto, a cloud can form. This explanation then begs the question as to why air parcels ascend in the atmosphere—the four main reasons are described below.

### Convection

Atmospheric convection relies on several physical processes:

- radiation from the sun heats the surface of the planet;
- conduction of this energy to air parcels near the surface results in their warming;
- the heated air parcels become buoyant and rise while they remain warmer and less dense than their surroundings.

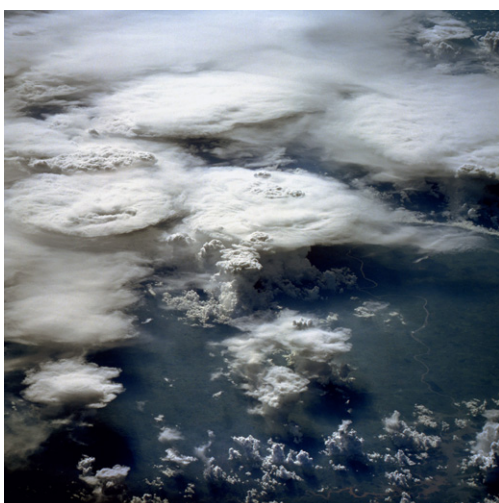
This is, for example, similar to the ascent seen in a lava lamp and is the mechanism most

often responsible for driving the development of cumulus clouds (figure 4). When this ascent has started, condensation will occur when the air parcel has cooled sufficiently, if CCN are present. As atmospheric conditions are often relatively uniform over quite large areas, groups of cumulus clouds are often seen together, all with flat bottoms at the same altitude, as the condensation starts at the same level over a large area. The gaps between the clouds are usually caused when the shadows of the first cumulus cells that form shade the ground and halt warming and convection in a limited area or, in the case of cloud streets, where organized cells become dominant.

Cumulus can grow to great heights and, in the case of cumulonimbus (figure 5), the convection can reach the tropopause (around 10–16 km, depending on latitude). The energy required for this growth initially comes from the convection but, in the latter stages, it also comes from the release of latent heat as water vapour condenses. The energy driving a cumulonimbus is extraordinary, with updraughts of up to 110 kph occurring. In the interface between these updraughts and downward-moving precipitation, electrons can be removed from particles in the cloud. This causes a charge dipole with the ground that is equalized by the release of lightning strikes.



**Figure 4.** Cumulus clouds from above (picture taken from an online Royal Meteorological Society collection called CloudBank [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).



**Figure 5.** Cumulonimbus photographed from space (source: NASA).

Vertical motion generally stops at the tropopause as there is a change from cooling to warming with height here (a temperature inversion) and the ascending air parcels are no longer buoyant. As a result, the cloud spreads out along the inversion into an anvil shape (figure 5). Smaller inversions are also often present in the

troposphere—figure 1 only shows the mean temperature profile. These inversions, or ‘lids’, can be a result of descending air masses or the remnants of previous weather systems. The impact of lids can be to stop convection before a cloud forms or to constrain the vertical development beneath a certain level. This is how the puffy expanse of stratocumulus is formed: condensation occurs just beneath an inversion and, when the convection cannot penetrate the lid, it simply spreads out and joins up beneath it.

### Frontal uplift

Whilst convective systems can drive the powerful and stunning cumulonimbus, frontal uplift is notable for the large scales, both in time and space, upon which it acts. From the surface, the typical clouds that result from fronts—stratus and nimbostratus—are uninspiring, block out sunlight and can bring hours of rain or drizzle. However, satellite imagery has the ability to show us the sheer size of these systems, with sheets of cloud sometimes covering the whole of the UK (figure 7). Furthermore, these systems can last for days on end, whereas a typical cumulonimbus will have gone through its entire life cycle in a few hours.

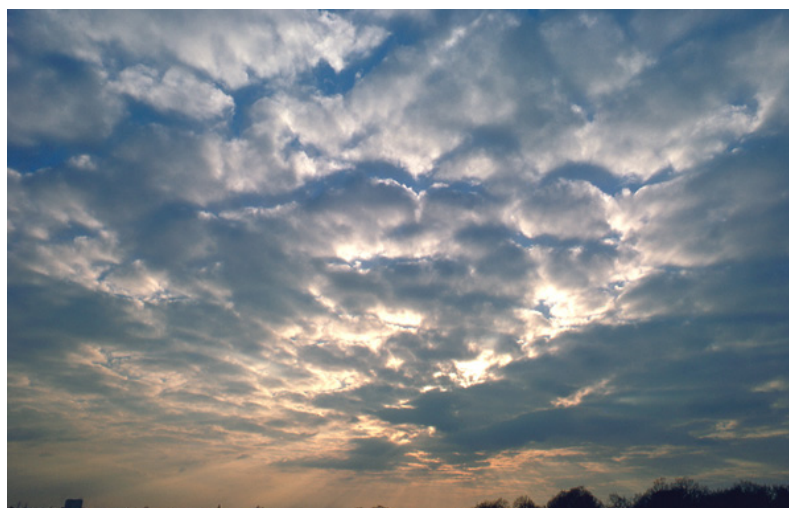


Figure 6. Stratocumulus (source: [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).

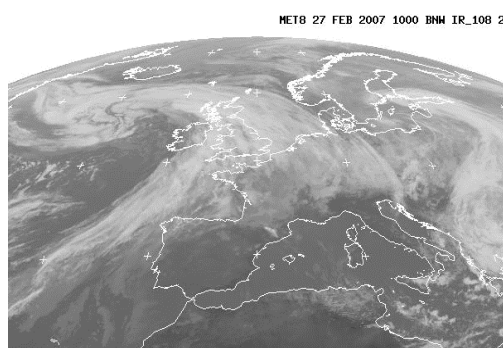
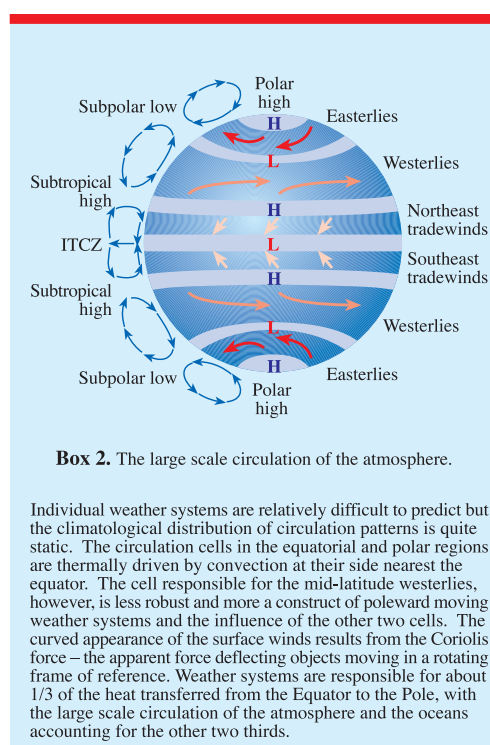
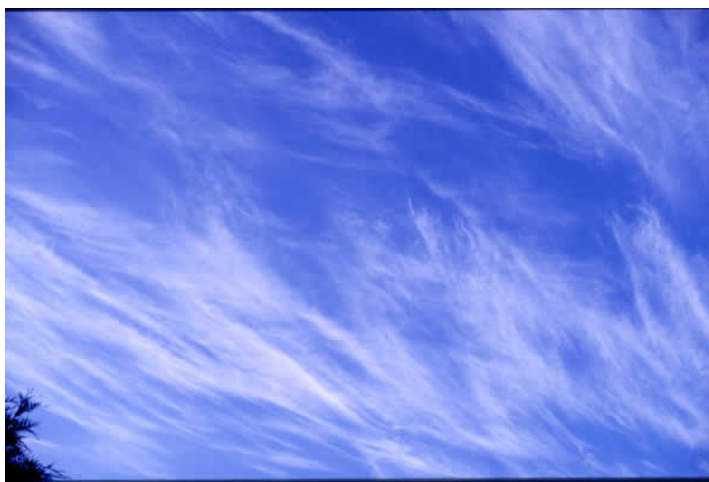


Figure 7. Satellite image (copyright EUMETSAT 2007) of the cloud associated with a frontal system over the UK.

So what drives these slow, large weather systems? The answer is the interaction between cold air masses and warmer, less dense ones. In particular, a cold front is where a mass of cold air slides under a warm one, forcing it upwards and, by contrast, a warm front is where a warm air mass slides over a cold one. This lifting can lead to vertical motion condensation over wide areas, as described above, and high into the troposphere, where higher-elevation clouds like cirrus (figure 8) or altocumulus form. Fronts are particularly common in the mid-latitudes, where interactions between polar air masses and warmer sub-tropical air masses (the Polar Front) are everyday occurrences in the mid-latitude



westerlies (box 2). Frontal systems also go through a relatively predictable life cycle of clouds, as was first described in the so-called ‘Norwegian model’ (see, e.g., <http://tinyurl.com/2cvhak>).



**Figure 8.** Cirrus is an ice cloud that often precedes a surface front (source: [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).



**Figure 9.** Altostratus lenticularis (source: [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).

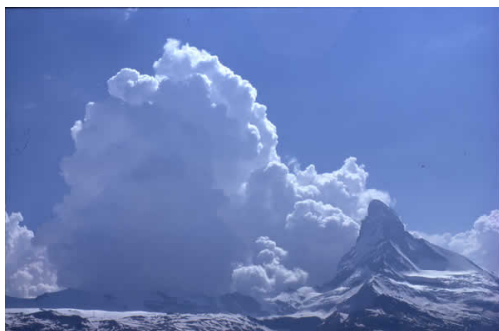
### **Orographic uplift**

Orographic uplift is quite similar to the process of lifting by a warm front in that the air mass is forced upwards when it meets an obstacle. Here, though, there is flow over rising terrain rather than a denser air mass. Precipitation is also often associated with this kind of lifting, and the term ‘rain shadow’ refers to the region of maximum precipitation just upwind of the terrain peak where most of the lifting occurs. Orographic effects also force two more unusual types of cloud. Lenticularis (lens-shaped; figure 9) clouds form in the regions of uplift driven by the atmospheric waves that are

created downstream of hills and mountains. Cap cloud, as the name suggests, forms over the tops of mountains. Whilst both these cloud types appear stationary, there is in fact a continuous flow of air through them—it is merely the region where the conditions for condensation are met that is not moving.

### **Convergence**

Convergence is simply where air masses move towards each other and, at the point where they meet, air is forced upwards. This mechanism is interesting because of the range of scales on which it operates. For example, convergence lines



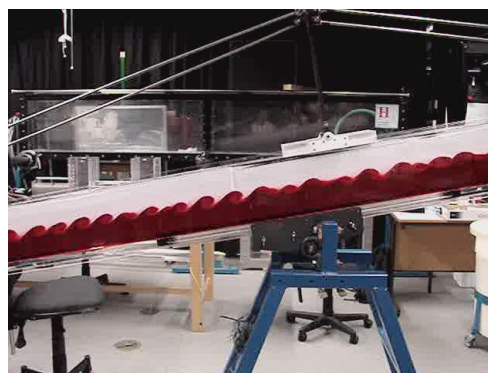
**Figure 10.** Orographic cumulus and the Matterhorn (source: [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).

are common downwind of the Cornish peninsula, where sea breezes from the north and south coasts meet. On a much larger scale, the Inter Tropical Convergence Zone (ITCZ; see box 2) is found where northern and southern hemispheric air masses meet in the equatorial region all around the globe.

### Unusual clouds

Kelvin–Helmholtz instabilities (figure 11) form in the atmosphere when layers of air flow across each other in opposing directions—a process known as ‘shearing’. Any small disturbance is rapidly amplified at the interface and results in a wave pattern.

This mechanism can be recreated in the laboratory by carefully layering water on top of



**Figure 12.** Kelvin–Helmholtz instabilities in the laboratory. This picture is taken from a video shot by Tor Smith (University of Leeds) at the Geophysical and Environmental Fluid Dynamics laboratory at the University of Cambridge (the full video can be viewed at [www.andrewrussell.co.uk/KHinstab.mpg](http://www.andrewrussell.co.uk/KHinstab.mpg)).

more dense salt water (that has also been coloured) in a long narrow tank. When the tank is tilted, the dense fluid flows downwards, which also forces the less dense fluid upwards. This creates shear and the development of instabilities (figure 12). The bottom of the tank needs to be slightly rough to introduce the necessary small disturbance.

Mammatus (figure 13) are quite an enigmatic cloud formation in that they are fleeting and poorly understood. They form most often, though not exclusively, on the underside of cumulonimbus anvils. It is thought that the downdraughts in the



**Figure 11.** Atmospheric Kelvin–Helmholtz instabilities (source: [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).



Figure 13. Mammatus (source: [www.rmets.org/cloudbank](http://www.rmets.org/cloudbank)).

cloud are countered by updraughts outside that give the individual cells their smooth surface. The reason why certain regions hang down, however, is less well understood.

### A perspective on clouds

In this article, the methods of atmospheric condensation and vertical motion have been introduced and illustrated. This overview is, however, quite simplified—often more than one mechanism will be responsible for forcing the development of any one cloud, but the information given here provides some of the ideas to understand the physics behind our weather systems.

Whilst the study of clouds can be quite frivolous and fun (see, for example, the Cloud Appreciation Society—[www.cloudappreciationsociety.org](http://www.cloudappreciationsociety.org)) this article has shown that they are nonetheless important, particularly in the climate system. Their development is both exciting and brings together many physical processes but, most interestingly, anyone can examine clouds and weather systems as they develop—and they are amazingly dynamic. Furthermore, with television broadcasts of weather predictions, a wealth of information freely available on the internet and meteorological instruments being quite cheap, it is a field where the analysis of conditions can be made with relative ease and where the results and implications of any study can be observed and experienced first hand.

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### Further reading

- Bohren C F 1987 *Clouds in a Glass of Beer* (New York: Wiley) p 185
- Pretor-Pinney G 2006 *The Cloudspotter's Guide* (Peterborough: Hodder & Stoughton) p 320
- Rogers R R and Yau M K 1996 *Short Course in Cloud Physics* (Woburn, MA: Butterworth-Heinemann) p 304



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