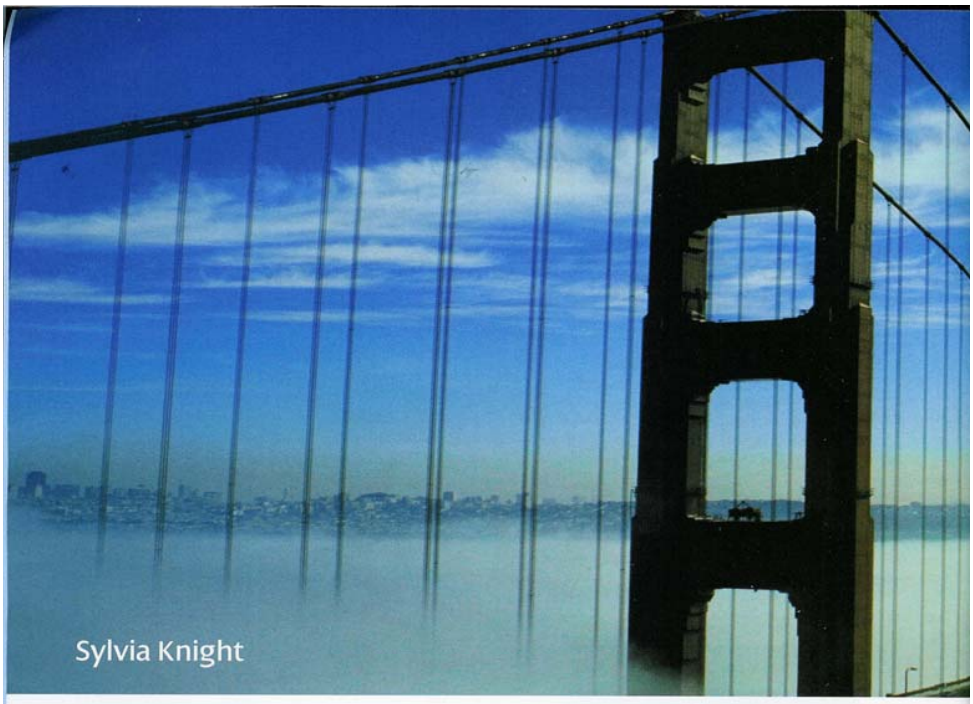


Sylvia Knight

Clouds are the most visual interaction that we have with the weather. They can be enigmatic and beautiful and a sign of fine or foul weather to come.

First of all, though, what are clouds? The simple answer is that clouds consist of water droplets (or ice crystals in the case of the highest clouds) typically about 0.02 mm in diameter — up to 10^{12} per cubic metre. These droplets have the effect of scattering light, which, in turn, makes them visible and appear milky-coloured. Clouds are generally only present in the lowest region of the atmosphere, the *troposphere*, which reaches up to around 10 km and in which temperature falls with height (see Figure 1).

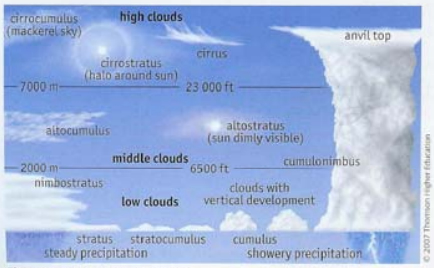


Figure 1 The main cloud types.

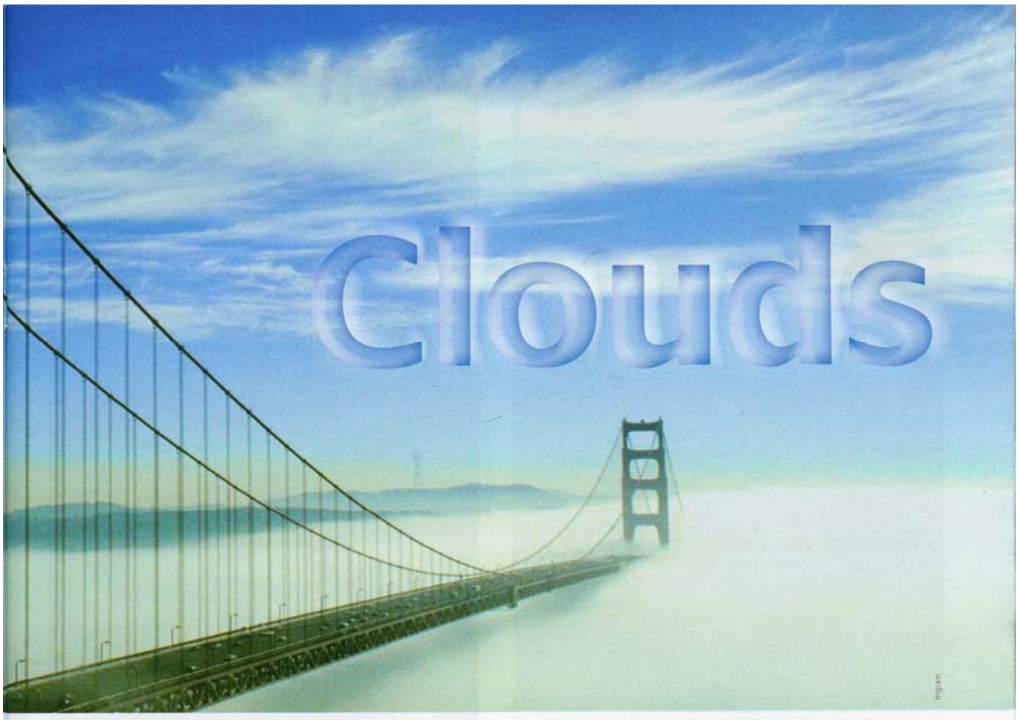
> **Physics focus**
>
> Ideas about **heating and cooling, gas laws,** and **rotational motion** help explain how the atmosphere moves and how clouds form.

In discussing cloud types it helps to have translations of the main Latin names:

- cumulus means 'little heap' and is used for 'fluffy' clouds
- stratus means 'layer' or 'sheet'
- nimbus originally meant 'bright cloud surrounding a god' and is now used to mean 'rain cloud'
- cirrus means 'fibre' or 'lock of hair'
- alto means 'high' (although, rather unhelpfully, it refers to mid-level cloud).

Clouds and climate

Clouds are responsible for the removal of certain pollutants from the atmosphere, and different types of cloud have different effects on climate. For example, some clouds reflect much of the incoming solar radiation and so cool the Earth. On the other hand, water vapour is a very effective greenhouse gas and so, in a warmer climate with more evaporation from the ocean, an increase in water vapour in the atmosphere would have a positive feedback on the climate. The representation of the amount and different types of clouds in the computer models



used to make weather and climate forecasts is not particularly good. All in all, the study of clouds is not a fluffy matter.

Cloud formation

Clouds form by the condensation of water vapour. Water vapour condenses more readily out of cold air than warm air, because less energy is available for evaporation. 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 relatively warm, moist air cools for one reason or another the air becomes saturated, the water vapour condenses and a cloud forms. The temperature at which this happens is known as the *dew-point* temperature.

However, reaching the dew-point is not sufficient for condensation to occur. Indeed, droplets cannot form spontaneously until the air reaches much lower temperatures, often below 0 °C, when the air is *supercooled*. Water droplets are much more likely to form where there are very small particles onto which the vapour can condense. Consider a sparkling drink. Although the drink is super-saturated with carbon dioxide, the gas does not all escape spontaneously when you open the can or bottle and pour the drink into a glass. If you look closely, you can see that bubbles can only form at places where there are imperfections or dirt on the surface of the glass. Points where the carbon dioxide changes phase and escapes from the drink are called nucleation sites. Try adding salt to the drink. This increases the number of nucleation sites and allows more bubbles to form. In effect, this creates a 'reverse cloud', with a cloud of carbon dioxide gas in the liquid drink.

CCN

In the atmosphere, typical particles (called aerosols) that act as **c**loud **c**ondensation **n**uclei (CCN) are dust, soot, sea salt, phytoplankton or sulphate and are usually about 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.

Pressure and temperature

In the atmosphere, clouds generally form when moist air cools as it rises to regions of lower pressure. If no heat is added to or extracted from the gas in this process, the first law of thermodynamics and the ideal gas law (Box 1) can be used to derive an equation describing the changes in pressure and temperature:

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^k \qquad (1)$$

where $k = 0.286$, T_0 and p_0 are the initial temperature and pressure of the air and T and p are the final pressure. From this equation, known as Poisson's equation, you can see that, if the pressure p increases, the air gets warmer, and, if the pressure decreases, the air cools.

Box 1 Ideal gas and the first law of thermodynamics

An ideal gas with pressure p in a volume V obeys the equation

$$pV = nkT$$

where T is the absolute temperature, n the number of gas molecules and k the Boltzmann constant ($k = 1.38 \times 10^{-23}$ J K^{-1}).

If some heat ΔQ is supplied to a gas, then energy conservation requires that

$$\Delta Q = \Delta U + \Delta W$$

This is a statement of the first law of thermodynamics.

ΔU is the increase in the internal energy of the gas; the molecules' kinetic energy increases and the temperature rises. ΔW is the work done by the gas as it expands. For example, if the gas expands at constant pressure and its volume increases by ΔV, then

$$\Delta W = p\Delta V$$

A process in which *no* heat is added or extracted is called *adiabatic* and now

$$\Delta U + \Delta W = 0$$

If a gas expands adiabatically, it will cool — like letting the air rapidly out of a bicycle tyre. ΔW is positive (the gas does work) but ΔU is negative (the molecules lose kinetic energy).

If the parcel rises and cools enough and there are CCN available, a cloud can form.

What makes air rise?

But what makes air rise? There are several mechanisms each associated with different cloud types. We'll look at each in turn.

Convection and cumulus

Atmospheric convection involves:

- radiation from the Sun heating the surface of the Earth
- conduction of this energy to air near the surface
- the heated air rising while it remains buoyant, i.e. warmer and less dense than the surrounding air

This is the mechanism usually responsible for cumulus clouds (Figure 2). A similar process moves the blobs of oil in lava lamps. 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 altitude where the temperature becomes low enough for condensation. The gaps between the clouds are usually caused when the shadows of the first cumulus clouds that form shade the ground and halt warming and convection over a limited area. Because land has a lower heat capacity than water and therefore heats up more rapidly, on very calm days you can sometimes see cumulus clouds forming over small islands but not over the surrounding sea.

Cumulus can grow to great heights and, in the case of cumulonimbus (Figure 3), the convection can reach the top of the troposphere. The energy required for this growth initially comes from the Sun warming the Earth's surface, but as water vapour condenses the latent heat released (Box 2) warms the air and allows it to rise further. Updraughts of up to 30 m s^{-1} have been measured. In the interface between these updraughts and downward-moving precipitation, electrons can be removed from particles in the cloud. This causes charge to build up in the cloud, giving rise to lightning strikes.

Figure 2 Cumulus clouds from above.

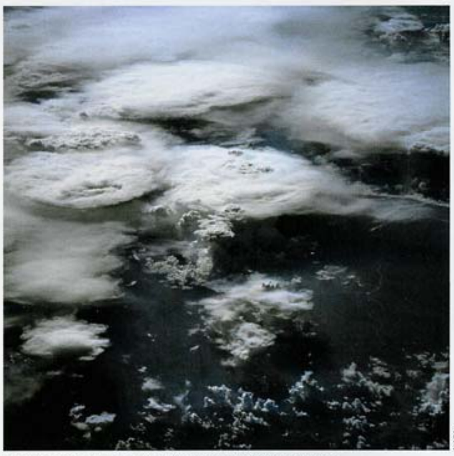


Figure 3 Cumulonimbus photographed from space.

Box 2 Latent heat

When a substance changes state (from solid to liquid or liquid to gas) it requires an input of energy that increases the molecules' potential energy without raising the temperature. This energy is known as latent ('hidden') heat. As the substance liquefies or solidifies, this same energy is given out while the temperature remains at the melting or boiling point.

For water at normal atmospheric pressure:

specific latent heat of fusion (melting) = 3.34×10^5 J kg^{-1}

specific latent heat of evaporation = 2.26×10^6 J kg^{-1}

Vertical motion generally stops at the top of the troposphere, where there is a change from cooling to warming with height (a temperature inversion) and the ascending air is no longer warmer than the surrounding air. As a result, the cumulonimbus cloud spreads out along the top of the troposphere into an anvil shape. Smaller inversions are also often present in the troposphere. For example, fog can form on clear nights when the ground loses heat to space by radiation more rapidly than the air. The air in contact with the ground cools by conduction, with the result that colder, cloudy air near the ground is trapped below warmer, clear air. Puffy expanses of stratocumulus (Figure 4) are formed when the condensation level is just below an inversion and the cloud simply spreads out under it.

Figure 4 Stratocumulus.

Frontal uplift and stratus

Whilst convective systems can drive the powerful and stunning cumulonimbus, frontal uplift produces vast, long-lived clouds. From the ground, typical frontal clouds — stratus and nimbostratus — appear grey and can bring hours of rain or drizzle. Satellite imagery can show us the sheer size of frontal clouds, which sometimes cover the whole of the UK (Figure 5) for days on end. In contrast, a typical cumulonimbus will go through its entire life cycle in a few hours.

Figure 5 Satellite image of the cloud associated with a frontal system over the UK.

Weather fronts

So what drives these slow, large weather systems? The answer is the interaction between cold air masses and warmer, less dense ones. Specifically, at a cold front a mass of cold air slides under a warm one, forcing it upwards, and at a warm front a warm air mass advances over a cold one. This lifting can lead to condensation over wide areas and high into the troposphere, where high clouds like cirrus (Figure 6) or altocumulus form.

Figure 6 Icy cirrus clouds often precede a surface front.

The term 'front' was first used just after the First World War to describe the 'battle' between the two air masses. Fronts are particularly common in the mid-latitudes, where interactions between polar air masses and warmer subtropical air masses are everyday occurrences.

Individual weather systems are relatively difficult to predict, but the average circulation of the atmosphere (Figure 7) is

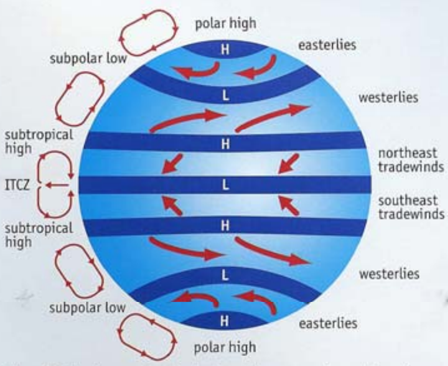


Figure 7 The large-scale circulation of the atmosphere. The red arrows show the surface winds.

Figure 8 A cap or 'tablecloth' of stratus on Table Mountain, Cape Town.

remarkably constant. It is the result of the fact that the tropics receive more solar radiation than the poles, and therefore heat has to be transported polewards. Weather systems are responsible for about one third of the heat transferred from the equator to the poles, with the large-scale circulation of the atmosphere and the oceans accounting for the other two thirds.

The curved paths of the surface winds result from the Coriolis effect (see Box 3). As air moves north or south from the equator it travels eastwards faster than the ground beneath it.

Orographic uplift, caps and lenticulars

The effect known as *orographic uplift* occurs where air is forced over an obstacle such as a mountain. (The term comes from the Greek *oros* meaning 'hill'.) Two unusual types of cloud are caused by orographic uplift. Cap cloud, as the name suggests, forms over the tops of mountains (Figure 8) whereas lenticular (from Latin *lenticularis*, lens-shaped) clouds form downstream. Although both these cloud types appear stationary, there is in fact a continuous flow of air through them — it is 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 is common downwind of the Cornish peninsula, where sea breezes from the north and south coasts meet. On a much larger scale, the intertropical convergence zone (ITCZ, see Figure 7) is found where northern and southern hemispheric air masses collide.

Last word

Anyone can watch the clouds as they develop, but scientists are still trying to understand the complex physics and chemistry that goes on inside them. While clouds are fundamental to the weather and climate that we experience, they can also be quite fun — see, for example, the Cloud Appreciation Society:

www.cloudappreciationsociety.org ■

Box 3 Coriolis effect

An object of mass m moving at velocity v in a curved path of radius r has *angular momentum* L:

$$L = mvr$$

Like linear momentum, angular momentum is conserved. Unless an external turning force acts, the angular momentum of an object (or a collection of objects) remains constant. Sit on a swivel chair and spin slowly with your arms and legs outstretched. If you then fold your limbs close to your body, you spin faster — you have reduced r so v must increase to compensate.

Think of a parcel of air at the equator, moving in a circle at the same speed as the Earth's surface beneath it. As the air travels towards the pole, the radius of its path becomes smaller. To conserve angular momentum, its speed around the circular path must increase so it travels eastwards faster than the ground beneath it. This eastward deflection of air moving towards the poles is called the Coriolis effect (see Figure 3.1).

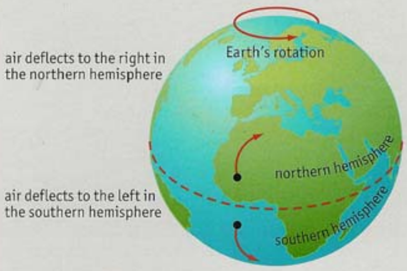


Figure 3.1 Coriolis effect.

Website

Royal Meteorological Society

www.rmets.org/

Sylvia Knight *is a meteorologist with a particular interest in climate modelling. She is Head of Education Services for the Royal Meteorological Society.*