Waves and weather

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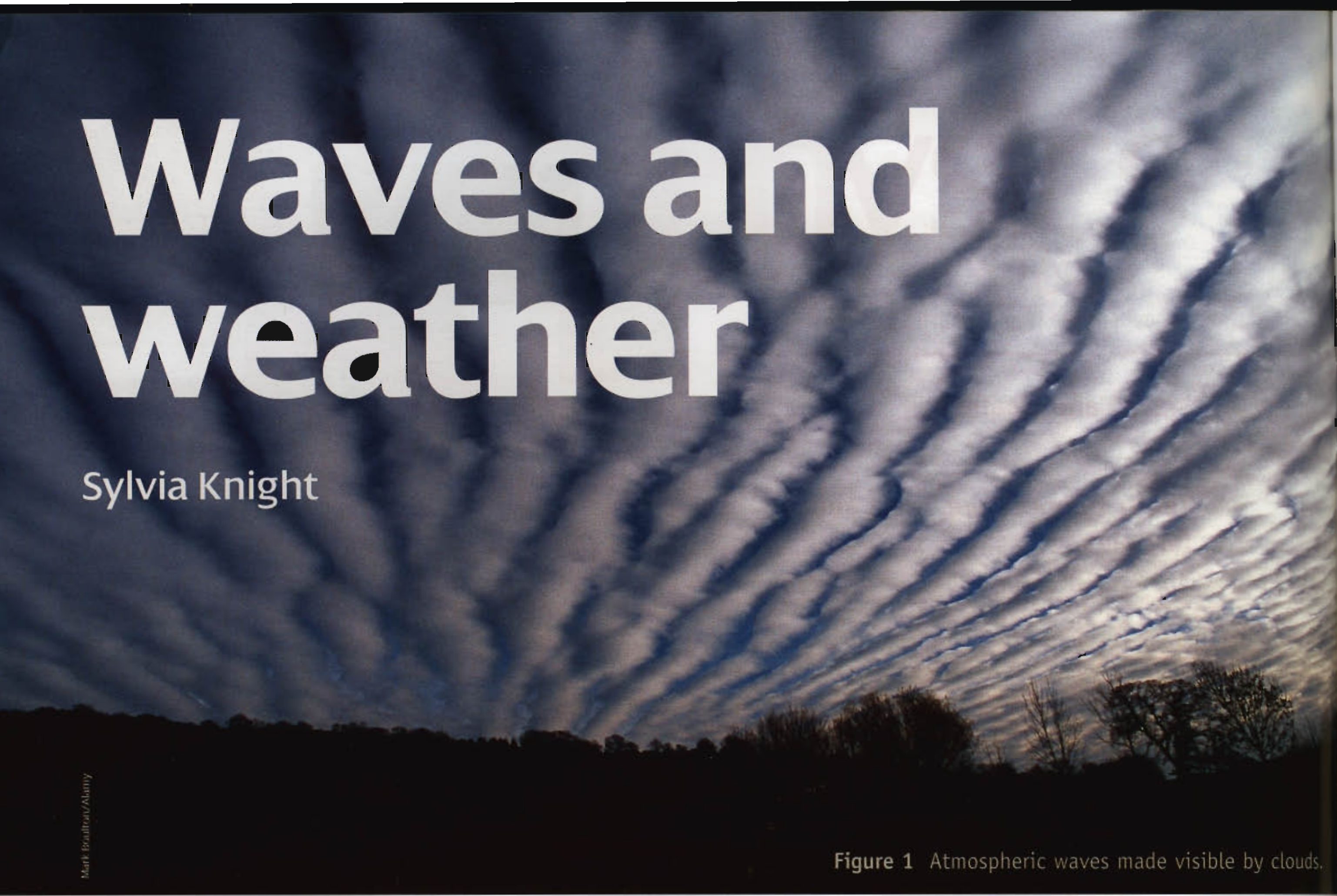

Mark Boulton/Alamy

Figure 1 Atmospheric waves made visible by clouds.

Physics focus

Atmospheric **waves** arise when parcels of air undergo **simple harmonic motion.** The atmosphere can be modelled as an **ideal gas**, which explains how clouds are formed that make the waves visible. The Earth's **rotational motion** drives the formation of the longest atmospheric waves.

Waves in the atmosphere have a major impact on the climate and weather we experience. They can transport energy and momentum over large distances. Their wavelength and amplitude range from small local disturbances (Figure 1) to large-scale disturbances in the global winds, where a few wavelengths take you round the Earth. Waves are responsible for the interaction between the upper and lower atmosphere, and for a lot of the interaction between different places on the surface of the Earth. For example, the reason why the El Niño/La Niña weather patterns in the tropical Pacific cause the entire planet to be anomalously warm or cold is the transport of information around the planet by large-scale waves. This article looks at some examples of waves in the atmosphere.

Mixing layers

On the ocean surface, waves develop when wind rucks up some water and gravity pulls it back down again — but it overshoots and a wave develops. In the same way, a velocity gradient and gravity produce a wave in the atmosphere. Figure 2 shows waves that occur when the higher air is moving faster than the lower. If the conditions are right, clouds will make the wave visible. The wave breaks (mixing the layers) when the crest of the wave is pushed ahead of the base, in the same way as ocean waves break as they approach the shore and the base is slowed by friction (see *Picture Page*, pages 16–17). Aeroplane condensation trails frequently break up in this way.

Mountain waves

When an air parcel approaches a barrier, such as a mountain range, it is forced to rise. As it does so, the pressure falls, the

Terry Robinson/Cloud Appreciation Society

Figure 2 Breaking waves mix layers in the atmosphere.

air expands and the temperature falls as the parcel has to work against its surroundings to expand (see Box 1). No heat is transferred to or from the air, so this process is adiabatic.

As the air cools, the rate at which water molecules condense increases and becomes equal to the rate at which water molecules evaporate. Eventually, the temperature of the air may fall below the point at which condensation exceeds evaporation and cloud can form (Figure 3). The top of the mountain may be covered in a cap cloud, and latent heat (Box 2) is released as the water vapour condenses. It may rain or snow.

Figure 3 Cloud formed upstream of the Matterhorn in rising air.

Downstream of the mountain, gravity is the restoring force that pulls the air, which is colder and more dense than the surrounding air, back down to Earth. Simple harmonic motion and a standing wave (Box 3 and Figure 4) are the result — air moves through the wave, but the crests and troughs and associated clouds remain in the same place. Lens-shaped clouds,

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 ($k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$).

If some heat ΔQ is supplied to a gas, 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 cools — 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).

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) = $3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$

specific latent heat of evaporation = $2.26 \times 10^6\,\mathrm{J\,kg^{-1}}$

Box 3 Simple harmonic motion

A system will oscillate with simple harmonic motion (SHM) if:

- there is a restoring force that, when the system is displaced, tends to restore it to equilibrium
- the restoring force is proportional to the displacement

A mass m undergoes SHM if suspended from a spring that obeys Hooke's law:

$$\boldsymbol{F} = -k\boldsymbol{x}$$

where $\boldsymbol{F}$ is the restoring force, $\boldsymbol{x}$ is the displacement from equlibrium, and k is the spring constant.

If the system does not lose energy (e.g. by the effect of friction), the mass will oscillate indefinitely, with a frequency f given by

$$f = \frac{1}{2\pi}\sqrt{\left(\frac{k}{m}\right)}$$

In the case of a packet of air in the atmosphere, squeezing the air into a smaller volume increases its pressure, giving rise to a restoring pressure that acts to return the packet to its original state.

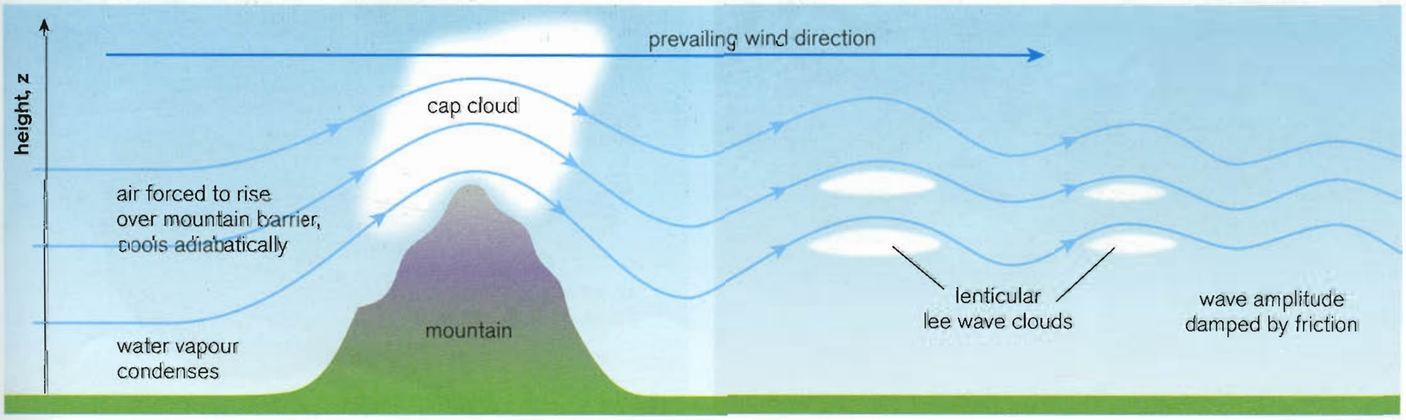

Figure 4 Waves form as air flows over a mountain.

called *lenticularis*, form at the crests of the wave (Figures 5 and 6). Friction gradually damps the wave downstream of the mountain.

As the air falls, it warms adiabatically again. However, if rain falls and removes water from the air, the latent heat taken up as the cloud droplets evaporate will be less than the latent heat released on the other side of the mountain, and so the air can end up warmer on the downstream side of the mountain than on the upstream side. This effect goes by many names — the Föhn wind in central Europe, the Chinook in the Rockies, and the Helm wind in the Cumbrian Pennines — and, when conditions become favourable, can cause the air temperature to rise by 20–30 °C in a few hours, melting any snow in its path.

In the atmosphere, the period of the oscillation is typically 10 minutes but depends on both the air temperature and the rate at which temperature changes with height. The more stable the air, the shorter the period of the oscillation.

If a parcel of air that is forced to rise, cooling adiabatically as it rises, ends up warmer than the surrounding air happens to be, it carries on rising, and the atmosphere is said to be unstable (the rate of change of temperature with height of the surrounding air is faster than it would be for adiabatic ascent). On the other hand, if it ends up cooler than the surrounding air, it tends to sink back down and the atmosphere is said to be stable.

Figure 5 Lenticular clouds in the crests of mountain waves.

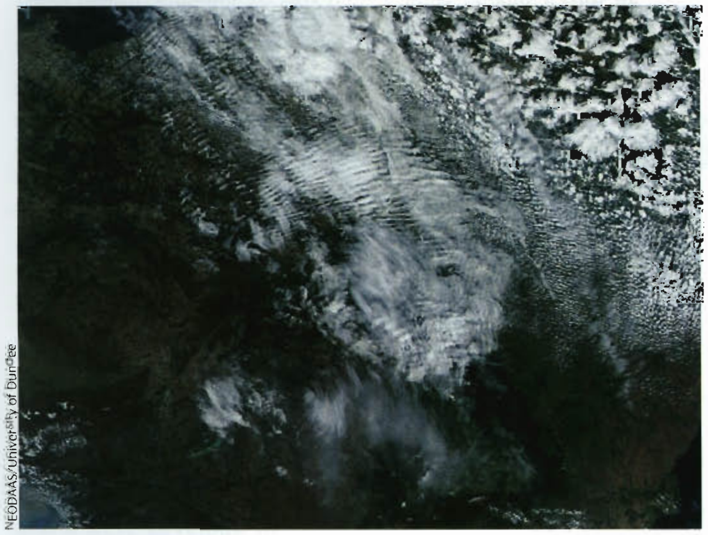

Figure 6 Mountain waves over the Carpathians.

Planetary waves

On the Earth's surface, the tropics receive more solar energy per unit area than the poles. This means that warmer air tends to rise in the tropics and cooler air tends to sink at the poles. If the Earth were not rotating, this would mean that air would flow equatorward at the Earth's surface, and poleward higher up, to complete the circulation. In fact, the Coriolis effect (Box 4) means that upper level air is effectively flowing eastwards in the mid-latitudes, and the circulation breaks down into two separate convection cells, the Hadley cell near the equator and the polar cell near the poles (Figure 7).

In the mid-latitudes (approximately 30–60° N/S), the convective cells driven by differences in the temperature of the Earth's surface break down, leaving strong jets of eastward blowing air. When these jets encounter large barriers, such as the Rocky Mountains or the Tibetan plateau, they are deflected and, because of the Coriolis effect and the need to conserve momentum, simple harmonic motion (see Box 3) develops.

Figure 8 shows the formation of a planetary wave (also called a Rossby wave). The boundary between the cold (blue) and warm (orange) air is marked by a cold or warm front, depending on whether the cold air is pushing into the warm, or vice versa. The result is a horizontal, transverse wave with 2–6 wavelengths circling the Earth (Figure 9). In the winter, both the

Box 4 The 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 v as the Earth's surface beneath it.

$$v = \frac{2\pi r}{T}$$

where R = 6370 km and T = 24 hours. 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 (Figure 4.1) is called the Coriolis effect.

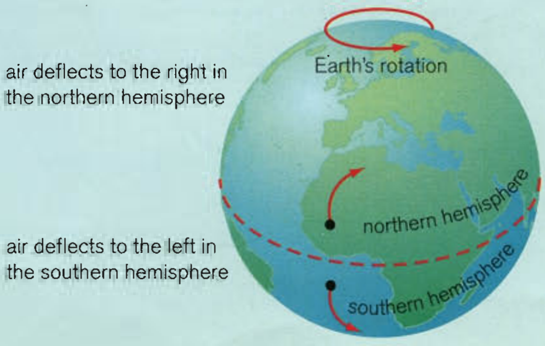

Figure 4.1 Coriolis effect.

wavelength and amplitude of the wave tend to be bigger than in the summer.

The high- and low-pressure systems that bring Britain most of its weather are associated with planetary waves. Figure 10 shows a radar image of rainfall over the British Isles. In this case, air blowing from the Atlantic is forced to rise over the Pennines. The band of rain over northern England and Scotland is over and upstream of the hills. Low atmospheric stability has produced a long-wavelength wave downstream. The radar shows that there is descent (clear air) over northeastern England and then ascent (with clouds and rainfall) over the North Sea.

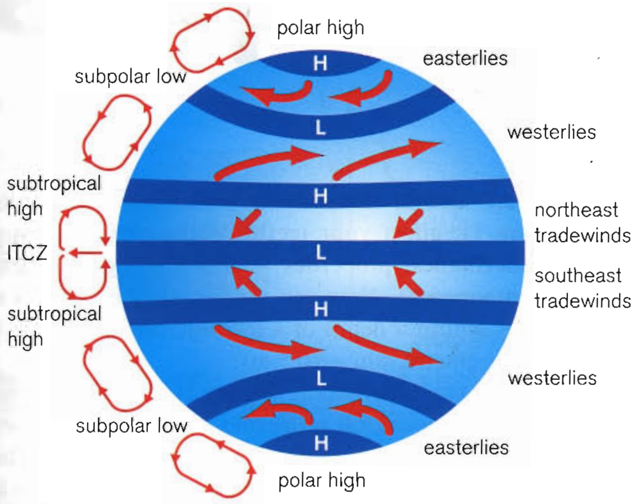

Figure 7 Large-scale circulation of the atmosphere. The red arrows show the surface winds.

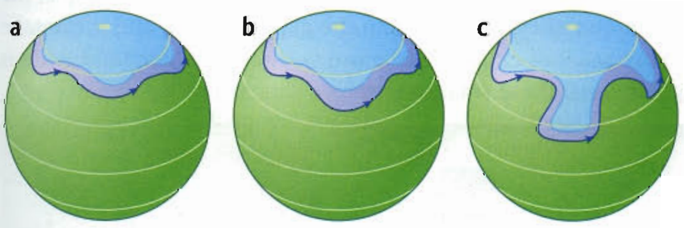

Figure 8 Planetary wave formation.

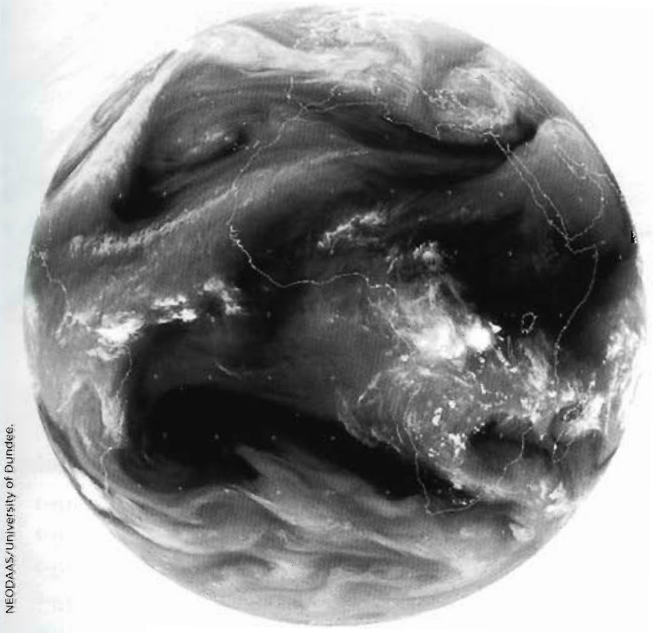

Figure 9 Satellite image showing a planetary wave around the South Pole.

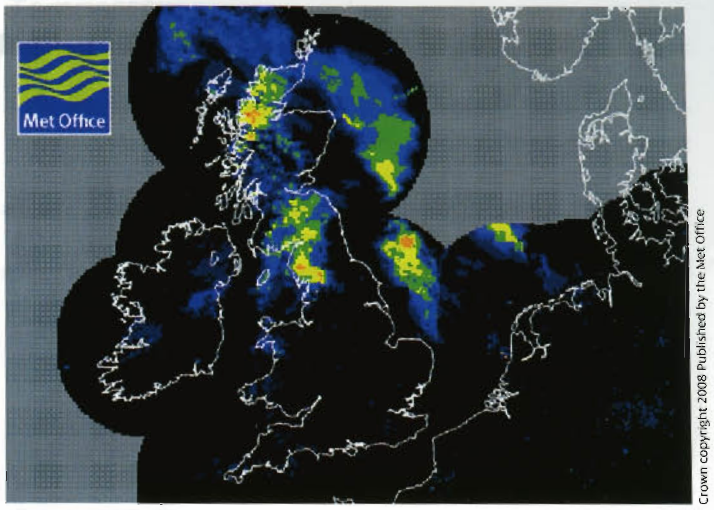

Figure 10 Rainfall over the British Isles.

Figure 11 Morning Glory.

And finally...

Waves in the atmosphere can result in stunning effects, some of which can only be seen from space and some of which can be seen from a back garden. Figure 11 shows the Morning Glory, a roll of cloud, up to 1000 km long, which can sweep over Northern Queensland in Australia in spring at up to 60 km h^{-1}. The cloud is a solitary wave or *soliton*, which has a single crest and moves without changing speed or shape. People travel a long way to surf the Morning Glory in gliders. ■

Websites

If you would like to see some more stunning cloud pictures, visit the website of the Cloud Appreciation Society:

www.cloudappreciationsociety.org

For general information about weather and climate, the website of the Royal Meteorological Society is a good place to start:

www.rmets.org

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