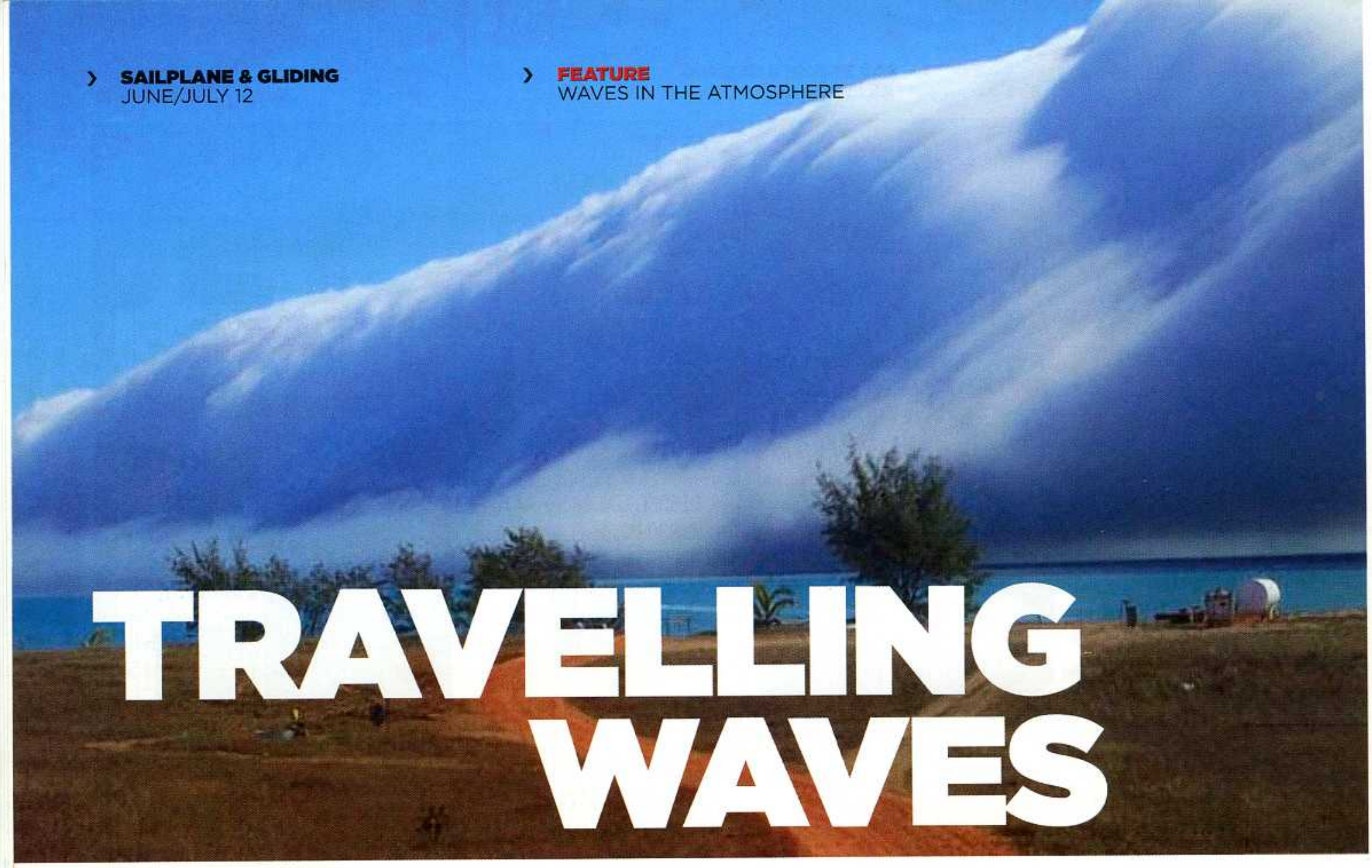
TRAVELLING WAVES



Morning Glory cloud (figure 5) seen from the surface approaching Sweers Island, north of Burketown, Australia (Russell White)

Alan Lapworth continues his series on waves in the atmosphere with a focus on travelling waves

A LAYER of air is said to be stable if the temperature increases with height or decreases with height at less than 3°C per thousand feet. Parcels of air in stable layers will tend to return to their original height if displaced up or down vertically so that the layer is 'springy' and will support internal wave motions. Such waves are known as gravity waves.

Gravity waves may be triggered by the flow of air over a ridge. Such waves are fixed relative to the ridge and are standing waves. They are useful to glider pilots because the updraughts are in a defined position and may even be made visible by clouds formed within them. However, in general, gravity waves are travelling waves, radiating horizontally and vertically from their source. If a glider passes through one, the pilot will notice a momentary lift or sink on the variometer, but will not be able to stay within the area of lift because the wave will have passed on. Very rarely a horizontally travelling wave may be made visible by a moving cloud formation and, in that case, a pilot might be able to travel with the wave and stay in a region of lift if the updraught is strong enough.

Figure 1 Severn Bore travelling up river. This bore can reach heights of up to six feet. The largest bore worldwide, in China, has recorded heights of more than 30 feet

River bores

Gravity waves are not the only type of coherent disturbance that can travel in a stable layer of air. Another type is the bore and this is analogous to bores that occur in some rivers when there is a strong incoming tide (usually a high spring tide) and the estuary funnels the tide, increasing its speed.

One well-known instance is the Severn bore, illustrated in figure 1. This bore can reach heights of over six feet, but the largest bore worldwide is probably that on the Qiantang River in China, where heights of over 30 feet have been observed.

A bore is a type of shock wave. It occurs when the speed of advance of the tidal front U relative to the river flow is greater than the speed of associated surface water waves. When this happens, the tidal water piles up above the surface level of the river outflow (figure 2). As the speed of water waves in shallow water is given by $\sqrt{gh}$ where g is the acceleration due to gravity and h is the flow depth, this will happen when $U/\sqrt{gh}$, known as a Froude number, is greater than one.

The form of the bore depends on the value of the Froude number. If it has a value less than two, the bore is a smooth series of waves, known as an undular bore. If it is four or five then it becomes a turbulent bore, sometimes referred to as an hydraulic jump.

The speed of travel of the bore can simply be determined by conservation of momentum flux through the jump. If the river flow is negligible then the speed of the bore U is given by:

$$U = \sqrt{\frac{gh_1(h_0 + h_1)}{2h_0}}$$

where h_0 is the river depth before the bore has passed and h_1 is the depth afterwards.

However, it can be shown that conservation of momentum flux means that energy is not then conserved across the jump and the excess energy has to be released into the water. In the case of the undular bore this may be by radiation of surface water waves away from the bore itself. In the case of a turbulent bore the excess energy generates the turbulence, which is thus an inescapable component of the bore. Although an undular bore looks like a surface wave, strictly it is different because in a bore fluid (in this case water) is transported with the bore along with energy, whereas, in a wave, only energy is transported. Generally the river flow in advance of the bore arriving is a fairly slack ebb current, but behind the bore there is a very rapid flood current, following the bore inland. A bore is sometimes confused with a soliton, which is a self-reinforcing solitary wave of a specific form and is a true wave.

Atmospheric bores

An exactly analogous phenomenon in the atmosphere occurs when a disturbance is given to a sharp inversion separating a layer of warm air overlying a colder layer. The two layers of air should be neither convective nor stable, but neutrally buoyant. In practice neither layer is likely to be exactly neutral, but a bore type of disturbance can propagate in any case.

To calculate the speed and Froude numbers of such internal bores, a reduced value of the gravitational acceleration, $\frac{g\Delta T}{T}$, where T is the absolute temperature and ΔT the temperature difference between top and bottom layers, must be used. Such atmospheric bores are relatively rare, but have been observed all over the world in the right conditions. In most cases, the disturbance initiating the bore is either a sea breeze or a thunderstorm outflow advancing under a stable inversion layer. These are both shallow layers of cold air running over a surface, lifting warmer air ahead of them.

A typical example is shown in figure 3 (below). This figure is based on measurements made of a sea breeze by instruments clamped to the tethering cable of a kite balloon. Temperatures are shown by coloured contours and air flow by streamlines. The sea breeze is obvious to the bottom right of the image, while in the top left the updraught ahead of the front has created a fairly small bore seen as a step in the upper inversion layer. This step is an atmospheric bore and may continue to propagate even after the sea breeze has died away.

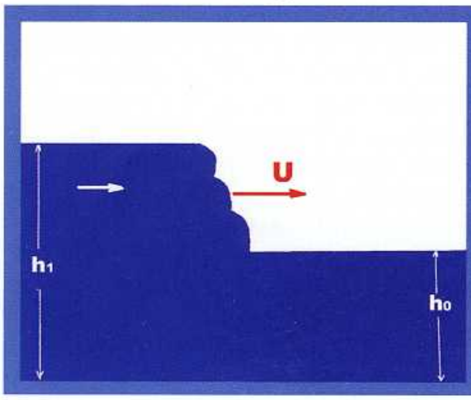
Atmospheric bores are most impressive when they are made visible by cloud, which will happen when the near surface layers are sufficiently moist.

They propagate forward at speeds which may be in excess of 30kts and the internal turbulence is clearly visible rising quickly on the front of the bore cloud and a downdraught behind. If the bore is undular, there may be secondary and tertiary waves following the primary bore. In appearance the bore cloud seems like a massive rotor and can certainly be as dangerously turbulent internally. However, there is a large area of smooth lift ahead of the bore and, in principle, it may be possible to soar in this provided a glider keeps ahead of the ➔

THERE IS A LARGE AREA OF SMOOTH LIFT AHEAD OF THE BORE AND, IN PRINCIPLE, IT MAY BE POSSIBLE TO SOAR IN THIS

Figure 6 Morning Glory cloud seen from the surface approaching Sweers Island (Russell White)

(Below, left to right) Figures 2-4: Schematic diagram of a bore travelling up river; sea breeze penetrating inland under an upper inversion in Holderness, UK, imaged by instrumental readings from a tethered balloon (colour contours are temperature, lines are flow streamlines); map of north eastern Australia showing gulf region with schematic line of Morning Glory (white dots) and direction of travel (red arrows) at around dawn



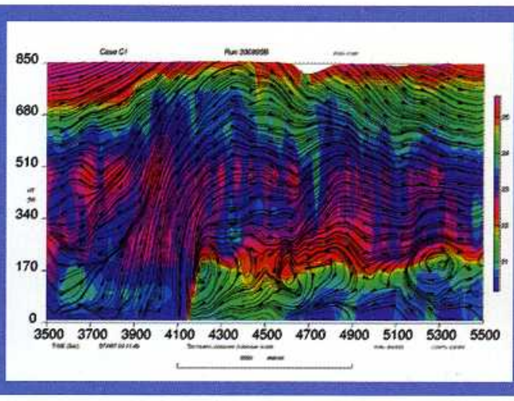


Figure 7: Morning Glory cloud seen from the air over sea approaching Kangeroo Point

Figure 8: Three Morning Glory clouds seen from above over Burketown

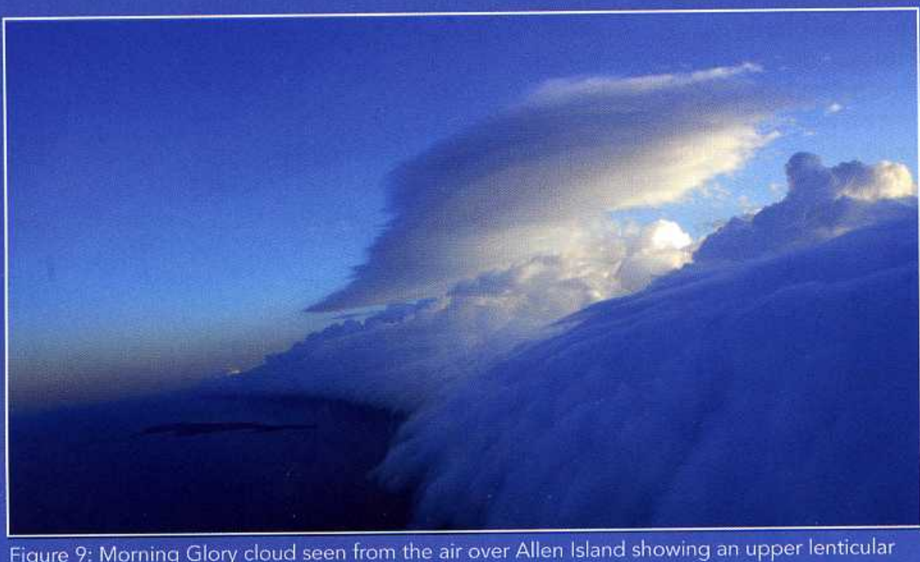


Figure 9: Morning Glory cloud seen from the air over Allen Island showing an upper lenticular cloud travelling with it (photos by Russell White)

fast-moving cloud. From the ground, a bore cloud can appear most impressive with a low cloudbase and high frontal wall moving fast towards the observer, with clearly visible rising turbulent updraughts.

Morning Glory

Although there have been worldwide reports of such bore clouds, they are rare in any one location and are generally unpredictable. However, in one part of the world they occur relatively frequently at a particular season. The area concerned is northern Queensland, Australia, and the season is the pre-monsoon months of September and October, before the start of the wet season. This is a very remote area and difficult to reach overland as the roads are unsealed dirt tracks and the country is a wilderness of desert scrub with crocodile infested rivers. There is an isolated settlement of Burketown in the region, having a population of a few hundred people and associations with the author Nevil Shute.

A map of the area is shown in figure 4 (overleaf). To the east is the Cape York Peninsula and this peninsula is important in the creation of atmospheric bores. In the hot weather, strong sea breezes form on both the east and west sides of the peninsula and roll inland. However, the prevailing south-easterly winds drive the east coast sea-breeze faster and, when the sea breezes collide, the resultant disturbance propagates westward as a bore on the marine inversion over the gulf of Carpentaria.

The bore continues westwards overnight and reaches the coast at Kangeroo Point on the coast north of Burketown by dawn. While travelling over the gulf, it is visible as a convective line of cloud as the upper air is unstable to moist ascent. However, as the southern end of the line approaches land, the cloud top becomes smooth as it penetrates the more stable overland air. The cloud line appears on about 40 per cent of days during the season. Its inland penetration to Burketown and beyond depends on whether a strong sea breeze has covered the area on the previous day. This is important because the sea breeze leaves a strong, low-level inversion behind it for propagation of the bore and, more important still, the near surface layer of air is moist. The moisture is necessary to feed the cloud that makes the bore visible.

These conditions are not often satisfied and a bore cloud, known to the locals as the Morning Glory will pass over Burketown itself only once every week or two on average. If it does so, it will then continue inland for