1 The nature of gravity currents

1.1 Introduction

Gravity currents, sometimes called density currents or buoyancy currents, occur in both natural and man-made situations. These currents are primarily horizontal flows and may be generated by a density difference of only a few per cent.

An important part is played in many different scientific disciplines by gravity currents. In the atmosphere, for example, most of the severe squalls associated with thunderstorms are caused by the arrival of an enormous gravity current of cold dense air. One such advancing atmospheric gravity current in the Sudan is shown in figure 1.1. In this case the dense air, which is moving from right to left in the picture, is clearly outlined by sand and dust which have been raised from the ground by the strong turbulent wind. The dust cloud is about 1000 metres high and the front is advancing at about 25 m s^{-1}; some idea of the scale can be gained from the houses which can just be made out in the distance.

Figure 1.1 The front of a gravity current of cold air in the atmosphere, made visible by suspended sand and dust.

Knowledge of the properties of these gravity currents is obviously important for aircraft safety. The fronts produce large changes in horizontal wind and areas of intense turbulence. As they are not always so clearly marked by dust as the example in the photograph, it is possible to fly into them without any warning. Encounters of this kind have been responsible for serious accidents, both at take-off and at landing.

Another, less intense, manifestation of atmosphere gravity currents appears in the sea-breeze front. These fronts form near the coast, and many of them propagate up to 200 km inland. They have important effects on the transport of airborne pollution, and also on the distribution of insect pests.

Avalanches of airborne snow, which are a severe hazard in the mountains, are gravity currents in which the density difference is supplied by the suspension of snow particles. For many years attempts have been made to reduce the damage caused by avalanches and there are research establishments devoted solely to the investigation of this special type of gravity current.

An industrial problem which has received much attention recently is the accidental release of a dense gas, which may be poisonous or explosive. Serious accidents have occurred in the resulting spread, which usually starts as a gravity current. Much experimental and theoretical work has been carried out on this problem, leading to possible methods of controlling such escapes.

Even in the home, problems with gravity currents are common. If the door of a warm house is held open for a few seconds on a cold day it is easy to detect the gravity current of cold air flowing along the ground into the house.

This open door experiment is recommended to the reader, who may care to use soap bubbles or puffs of smoke to detect the sudden onset of the gravity current of dense cold air after the door has been opened. This topic is dealt with in more detail in Chapter 14.

In the ocean, large volumes of warm or fresh water, less dense than the neighbouring salty water, flow as gravity currents along the surface. Gravity currents in the ocean are not as obvious to the casual observer as some atmospheric gravity currents, but lines of foam and debris on the surface may point to their presence. These lines are caused by the convergence of the flows there, and are well known to fishermen, since these currents have important effects on the distribution of fish.

Fresh-water gravity currents often flow along the surface in estuaries and fjords, above the more dense sea water. Figure 1.2 shows an echo-sounding of such a surface flow, made in the Fraser River in Canada. This shows the cross-section of a gravity current of fresh water advancing from the right, above the denser salt water from the sea. The leading edge of this current has a 'head' which is deeper than the following flow, a feature which is seen in most gravity currents.

The oil slick is an example of a man-made environmental problem. An oil spillage from a ship forms a non-mixing gravity current of less dense fluid on the sea surface. It is important to understand the development of this flow and find possible methods for both its containment and its dispersal.

1.2 Dam break

To understand the physics of a gravity current it will help to consider what happens when the wall of a dam breaks and releases the water behind it.

A mass of suddenly released water will start to collapse and flow horizontally. The main force acting on the water in such a flow is due to gravity, and acts vertically downwards. This results in a downward motion of the water which can only occur if the water spreads horizontally. So the potential energy of the water due to its height is continuously converted into the kinetic energy of the horizontal motion.

If the flow spreads mainly in one direction, for example along the bottom of a valley, a rough idea of the velocity, U, in that direction can be obtained by equating the values of the potential energy loss and the kinetic energy gain, i.e.

$$(mU^2)/2 = mgH/2$$

or

$$U = \sqrt{(gH)}$$

where m is the mass, $H/2$ the mean height of the centre of gravity and g the acceleration due to gravity. If for example the water was originally 20 m deep, the velocity would be about 14 m s^{-1}, or roughly 30 mph.

Viscous forces in the fluid can also have important effects. Viscosity may be likened to friction, in that a viscous fluid exerts retarding forces on those parts of itself which are trying to move with greater velocity than the rest, just as retarding forces due to friction occur between two solid surfaces in relative motion. The lower layers of the water in the dam-break flow are retarded by the

Figure 1.2 An echo-sounding made in the Fraser River in Canada. The front of a gravity current of fresh water is moving above sea water. (Courtesy of David Farmer.)

ground, and have a considerable effect on the form of the leading edge of the fluid.

1.3 Gravity currents

The water in a dam-break flow is submerged in the atmosphere, but this has only a very small effect on its behaviour. If the air is replaced by a fluid which is only a few per cent less dense than the collapsing fluid, then the flow will be different.

If in this 'dam-break analogy' flow the density difference between the two fluids were only 1%, the effective driving force would then have been reduced to only 1% of normal. Unless the coefficient of viscosity is large, or the scale is very small, the main controlling forces will be gravitational and inertial, due to the displacement of the fluid around the advancing current. Due to the net gravitational acceleration of the collapsing fluid being now only $g/100$, the previous dam-break flow will be replaced by one appearing to move 'in slow motion'.

A typical *gravity current* of dense fluid is now moving forwards into a slightly less dense fluid. In this case its rate of advance U can be approximated by

$$U=(gH/100)^{\frac{1}{2}}$$

or, in general, if ρ is the density of the less dense fluid and $\Delta\rho$ is the density difference,

$$U=\left(\frac{\Delta\rho}{\rho}gH\right)^{\frac{1}{2}}$$

The term $g\,(\Delta\rho/\rho)$ will usually be denoted by the symbol g', and called 'reduced gravity'.

The fluid in a gravity current may be chemically different from the surroundings and have a different molecular weight, but often the difference in specific weight that provides the driving force is due to dissolved material or to temperature difference. The large-scale gravity current in the atmosphere shown in Figure 1.1 was caused by temperature differences. If the temperature was about 12°C, this would give a density difference of about 4%. The value of g' will be 0.39 m s^{-2}. With a current height of 1000 m, we would expect the rate of advance to be about $(g'H)^{\frac{1}{2}}$ which is just under 20 m s^{-1}.

1.3.1 Suspension flows; turbidity currents

One way in which the overall density of a fluid can be increased is by the suspension of many small dense particles within it. Such suspension currents may be formed in various ways. One of the most important processes is the raising of material from the ground and its suspension by the turbulence within a gravity current. This suspended material increases the density and hence the speed and turbulence within the current. The process can thus become 'self stoking' in a current on a slope, further increasing the strength of the current. An example of such a suspension current is shown in Figure 1.3. This illustrates a suspension current of kaolin in water advancing through water towards the camera in the laboratory. This photograph shows very clearly the complicated shifting instability patterns manifested by a gravity current advancing along a plane surface.

Self-stoking gravity currents containing suspended matter also occur in the ocean. They start on slopes near the coast as mud-slides which increase in intensity until a suspension current is formed. These *turbidity currents* may become large enough to travel at speeds of over 30 m s^{-1}. They can gouge out vast channels in the sea bed and their progress has been followed by monitoring the successive breaking of submarine telephone cables, showing that they can travel for hundreds of kilometres.

1.4 Bores

A related phenomenon is the *bore*, which is also concerned with mass transport and has many features in common with the gravity currents already described.

The best-known type of bore is a tidal disturbance which moves upstream in some rivers and may be very violent at spring tides. It is an example of a hydraulic jump in which there is a sudden increase of the water depth associated with a change in the flow rate.

If the increase of depth at the front of a bore is less than about a third of the undisturbed water depth, a series of smooth waves appears at the leading edge and the bore is called 'undular'. For larger steps the tidal bore is turbulent and it advances as a wall of tumbling breakers; the structure is similar to that of breakers advancing towards the sea-shore.

Bores appear in rivers where the tidal range is large and the form of the estuary is suitable. Conditions are favourable in several rivers in England: on the River Severn the bore has been ridden by experienced surfers and journeys of

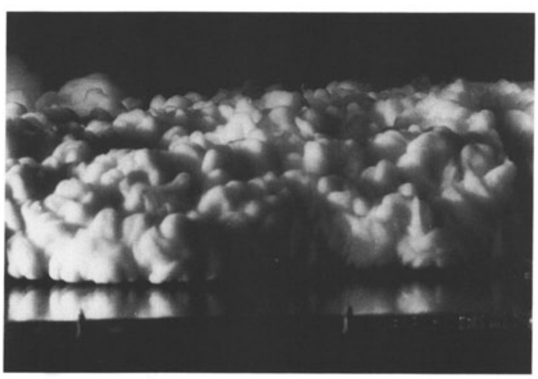

Figure 1.3 A suspension current in the laboratory, advancing towards the observer. (Courtesy of J.H.R. Allen.)

Cambridge University Press
978-0-521-66401-1 - Gravity Currents: In the Environment and the Laboratory: Second Edition
John E Simpson
Excerpt
More information

two or three miles have been achieved. However, since they are produced by tides, surfers who miss their moment may have to wait over 12 hours for the next breaker! Figure 1.4 shows a rider on a surf board using one of the waves at the front of the Severn bore. The bore shown here is an undular one, but breaking waves are forming in the shallower water near the banks of the river.

The conditions ahead of a hydraulic jump or a bore can be related to those behind it in a simple mathematical treatment.

In figure 1.5 the jump is shown brought to rest in a moving frame of reference; h_1, U_1 and h_0, U_0 are the height and velocity on the two sides of the jump.

Figure 1.4 A surfer on the advancing bore on the River Severn. (Courtesy of the Severn–Trent Water Authority.)

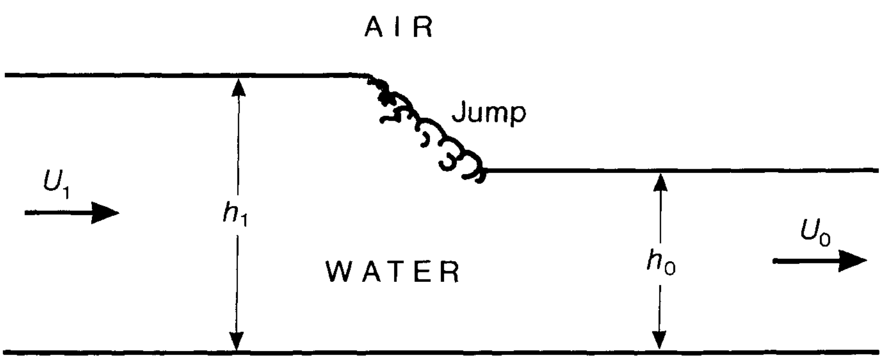

Figure 1.5 The flow through a hydraulic jump. The axes have been taken to bring the jump to rest, and h_1,U_1 and h_0,U_0 are the height and the velocity on the two sides of the jump.

The volume flux Q per unit width, passing in unit time, is, since mass is conserved,

$$Q = U_0 h_0 = U_1 h_1$$

A change in momentum across the jump is caused by the pressure difference. If density is ρ, since mean pressures at both sections are $g\rho h_0/2$ and $g\rho h_1/2$, the equation of momentum is

$$Q(U_1 - U_0) = g(h_1^2 - h_0^2)/2$$

hence

$$Q^2 = g h_0 h_1 (h_1 + h_0)/2$$

The energy, however, does not balance and the loss of energy per unit time is

$$\rho(U_0^2 - U_1^2)/2 + g\rho(h_0 - h_1)$$

which can be shown to be

$$g\rho(h_1 - h_0)^3/4h_1 h_0$$

This loss of energy, which must occur at a bore, is mostly effected in the undular case by the waves, each of which carries energy as it moves away from the front. The more intense bores cannot carry away enough energy by this method and the energy excess is dissipated by turbulence in the tumbling breakers at the leading edge.

1.5 Internal bores

The previous section considered bores at the free surface of a water flow. A somewhat similar class of internal bores can be formed at an interface between two fluids, one lying on top of another which is perhaps only a few per cent denser. Compared with surface bores, these internal bores appear to move 'in slow motion', since the buoyancy forces are very much reduced.

Internal bores have been described theoretically and investigated in laboratory experiments. Figure 1.6 shows such an experimental arrangement in which an obstacle is towed along the bottom of a tank containing a two-fluid system. The obstacle is moving to the right and displacing an undular internal bore which steadily moves along the interface ahead of it. If the moving obstacle is replaced by an advancing gravity current of dense fluid a similar effect can be produced.

Such experiments have been very helpful in understanding the physics of undular bores and will be described in more detail in Chapter 13.

During the last few years, internal bores have provided an explanation for an increasing number of phenomena in the environment, both in the ocean and in the atmosphere. They may for example be formed in the ocean by tidal effects on fresh-water layers near the coast. In the atmosphere they are formed in dense stable layers by advancing flows of cold dense air from thunderstorms, and they are also associated with sea-breeze fronts.

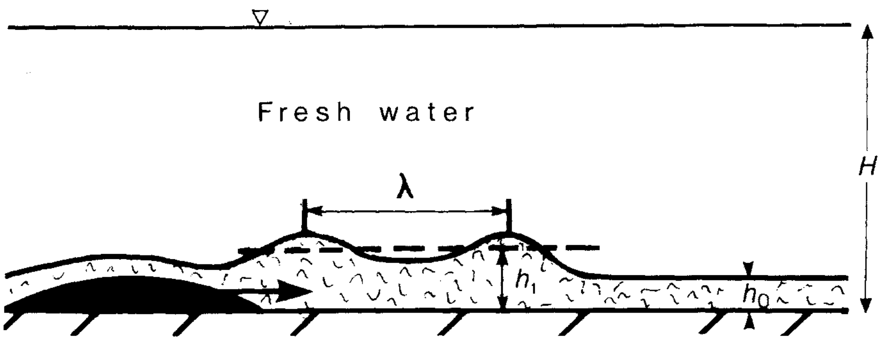

Figure 1.6 The production of an internal bore by a moving obstacle (black) in an experimental laboratory tank, in which a layer of fresh water (clear) lies above salt water (shaded). The bore is moving to the right along the interface between the two fluids, faster than the moving obstacle.

Figure 1.7 Clouds marking an undular internal bore in the atmosphere, the 'Morning Glory' in North Australia. (Courtesy of Roger Smith.)

When the ratio of the height h_1 behind the jump (see figure 1.6) to that in front of it, h_0, is less than about 2, then the internal bore is undular. In much deeper internal bores the leading edge is turbulent and appears very similar to the front of a gravity current. The photograph in figure 1.7 shows the clouds forming at an atmospheric undular bore in Northern Australia. This phenomenon appears in the early morning and is marked by a spectacular roll of cloud; its striking appearance has led to its name, the 'Morning Glory'.

1.6 Solitary waves

'Gravity currents' and 'gravity waves' are sometimes confused and the distinction between them is not always apparent. Here the name 'gravity current' will be applied to a phenomenon in which there is a clear transfer of mass (usually horizontal). In gravity waves there is little transfer of mass and the main transport is that of energy.

An undular bore, as has been noted, consists of an increase in depth of a fluid advancing with a series of waves on its surface. Closely related is the 'solitary wave' which is another shallow-water phenomenon, i.e. a disturbance which is high compared with the undisturbed depth. A solitary wave is not a

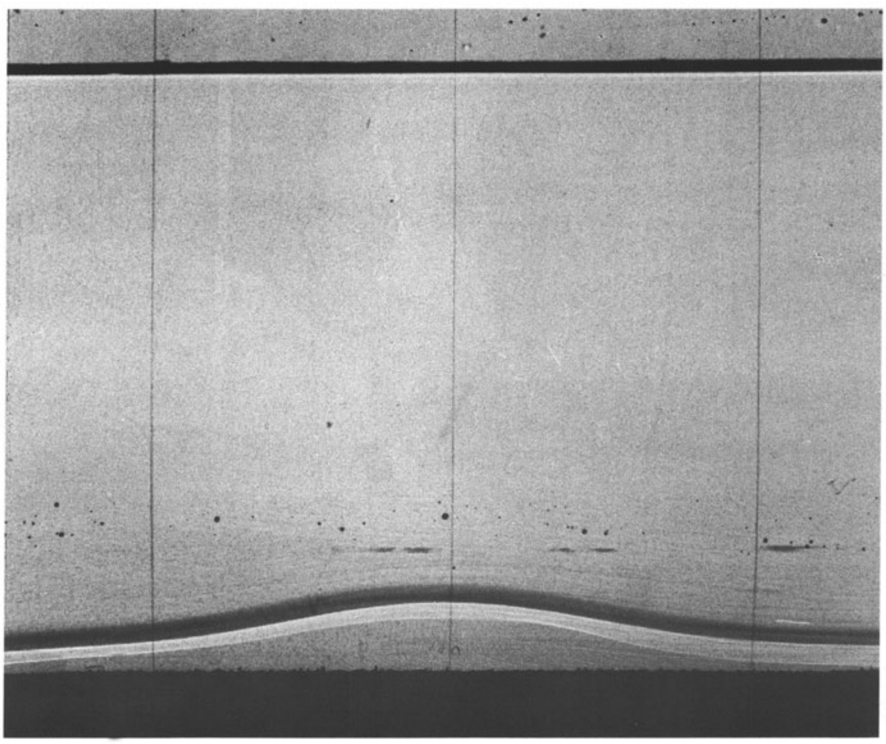

Figure 1.8 Internal solitary wave moving along an interface between two fluids in a laboratory tank.

periodic wave but consists of a single symmetrical hump which propagates at uniform velocity without change of form.

Scott Russell in the 1840s investigated solitary waves on the surface of a canal. On horseback he was able to follow examples of such waves for several kilometres and he showed that, with length, depth and amplitude properly matched, a solitary wave can propagate virtually unchanged, except for small effects due to bottom friction which reduce the size of the wave.

Internal solitary waves can exist at an interface between two fluids of different density. Examples occur in the atmosphere, where solitary waves have been observed on stable layers, moving steadily away from the distant disturbances which generated them. What is observed on the ground is somewhat similar to the arrival of a bore, with a line of cloud and a gust of wind, but in this case with only a temporary increase of surface pressure.

In the laboratory these internal solitary waves are very easy to create. Figure 1.8 shows an example of an internal solitary wave formed at a layer which had been laid down by a gravity current. When the gravity current reached the end of the tank some of the dense fluid ran up the wall and then descended as a mass which generated the solitary wave shown, moving from right to left. When this disturbance reached the other end of the tank, three metres distant, it was reflected and returned with nearly the same shape and speed.