

7

Gravity currents in rivers lakes and the ocean

Sharp boundaries form in the ocean between adjacent water masses of different density associated with differences in temperature, salinity or amount of suspension and appear at the surface as frontal lines.

Pioneering descriptive and dynamic studies of fronts were made in the seas around Japan, where fronts were classified according to the area where they formed (Uda, 1938). Much descriptive material was gathered from Japanese fishermen, who often noticed a visible line of demarcation at the boundary between water masses. The sea can become quite violent in frontal zones, especially if the current shear across the front is large. Steep pyramidal standing waves may form when wave trains cross into a region of impeding current, or where a strong current flows in a direction opposite to a strong wind.

Flotsam often accumulates along the convergence line, and may include detritus such as dust, foam, timber and examples from the whole food chain up through plankton, mollusca, insects, fish, birds, whales and finally humans (in the form of fishermen and also corpses!)

7.1 Ocean-scale fronts

Many oceanic fronts are formed at the boundaries of two water masses having different origins, and are of sufficiently large scale to be influenced by the earth's rotation.

A large-scale front is formed at the boundary of the northwestern spreading of the gravity current of warm blue Sargasso Sea water flowing over the underlying cold green waters of the North Atlantic. The Gulf Stream is a warm surface current flowing parallel to this boundary, partly due to rotational forces and partly caused by the westerlies and the trade winds. The map in figure 7.1 shows a record of the position of the thermal front of the Gulf Stream during a nine-month period between February and November 1978.

7.1.1 Shallow-sea fronts

Small-scale counterparts of oceanic fronts are found in coastal waters and may result from tidal mixing or from the interaction between fresh and salt water. Figure 7.2 shows a satellite photograph of Britain in which differences in sea surface temperature indicate two such fronts.

The structure of a similar front investigated by Pingree (1974) near the Channel Islands is shown schematically in figure 7.3. This shows two water types A and B separated by a frontal region. Near the front there are convergent motions which sweep all floating material to the edge of the front. Confirmation

Figure 7.1 Temperature discontinuities in the NW Atlantic. The lines show the variability of the thermal fronts of the Gulf Stream through a nine-month period. (After G.A. Maul.)

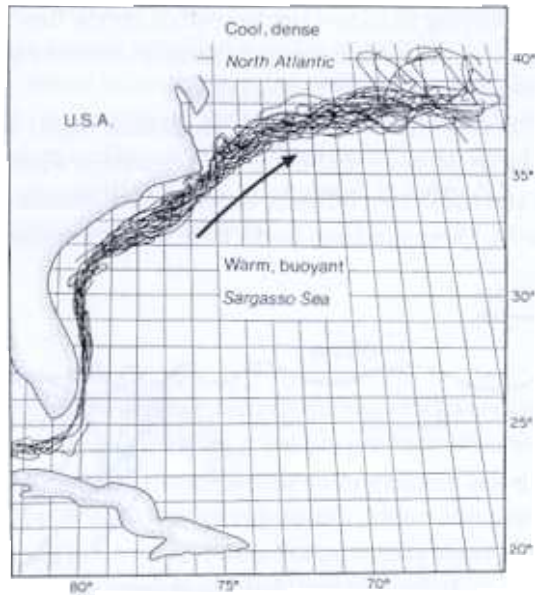
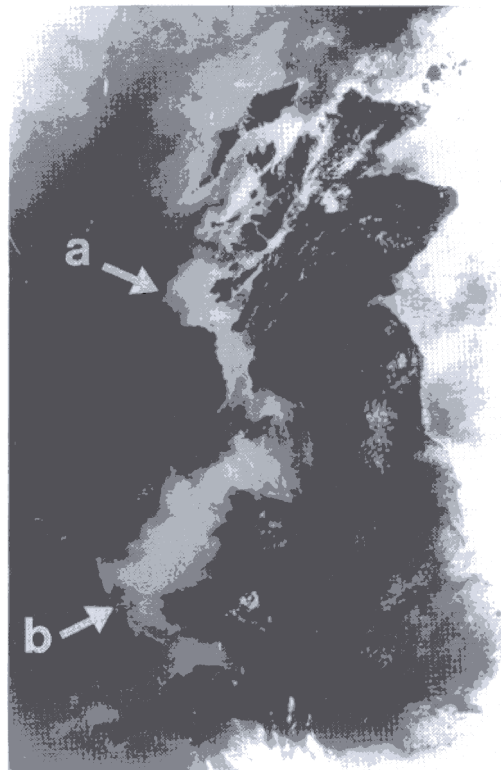


Figure 7.2 Satellite photograph showing fronts in the sea near Britain. (a) Islay-Malin head front, (b) Celtic Sea front. (Courtesy of Dundee University Electronics Laboratory.)



of sinking motions was made by marking the sea surface along one side of the front with a fluorescent dye. This line was seen to move towards the front, deform as shown and disappear beneath the surface.

The flow observed appears to be that of a surface gravity current, as described in section 12.6. The less dense fluid, B, advances relative to the water mass A, forcing surface water beneath it. As the flow from both sides is towards the front, any objects close to the surface will move towards this line, and if sufficiently buoyant will collect there.

These shallow-sea fronts or 'shelfbreak' fronts are commonly formed at boundaries between shallow nearshore waters, which are mixed by winds or tides, and the deeper offshore waters, which remain stratified as shown in figure 7.4. These shelf-sea fronts form in shallow water where tides generate

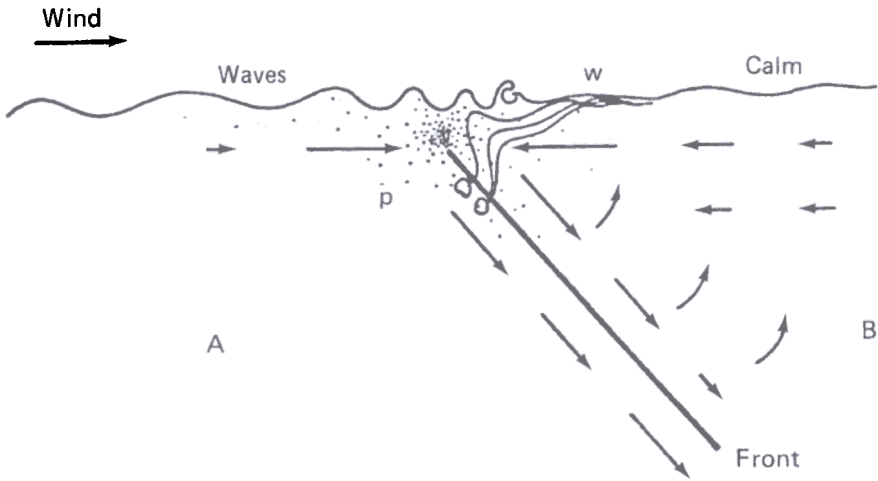


Figure 7.3 A schematic picture of the cross-section of a front separating two water masses A and B. The dots show water-borne material which collects in area w. (After Pingree, 1974.)

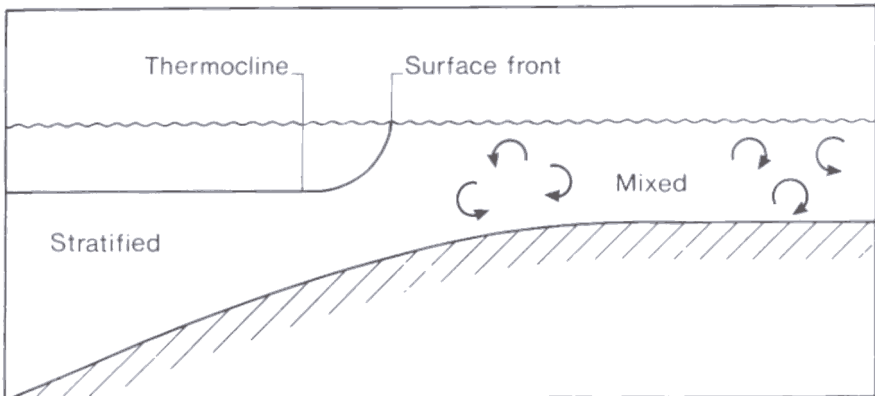


Figure 7.4 The formation of a 'shelfbreak front'. The bottom-generated turbulence prevents the formation of the seasonal thermocline.

enough turbulence at the sea-bottom to prevent the formation of a sharp thermocline.

It has been shown that an important parameter governing this kind of front formation is u^3/h , where u is the strength of the tidal stream and h the depth of the water (Simpson & Bowers, 1981). The rate of work done by the turbulent kinetic energy is proportional to u^3 , and the rate of change of potential energy it produces in mixing stratified water is proportional to the depth h . So in areas mixed by strong bottom-generated turbulence, as on the right in figure 7.4, u^3/h is large. In the area on the left, u^3/h is small, and the area remains stratified. Critical values of this parameter have been shown to appear in the frontal areas which appear in the satellite photograph in figure 7.2, namely in the Celtic Sea and near the Scilly Islands.

7.2 Fronts in estuaries

An estuary, the zone of transition between a river and the sea, can have many possible flow regimes. Large tidal stream velocities tend to produce estuaries vertically mixed through the action of bottom-generated turbulence. A high discharge rate of fresh water can lead to significant stratification, reducing the amount of mixing and resulting in a two-layer flow. Frequent new observations of small-scale fronts in estuaries are being made and their biological importance is now being recognised. A comprehensive review by O'Donnell (1993) describes field observations and laboratory experiments, with theoretical models.

One possible configuration in a river with high discharge rate but low tidal currents is illustrated in figure 7.5. Fresh water flows down the estuary over a 'salt wedge' formed by the opposing dense salty current. Both the front of the fresh-water river plume and the salt wedge on the river bed can be maintained throughout the tidal cycle.

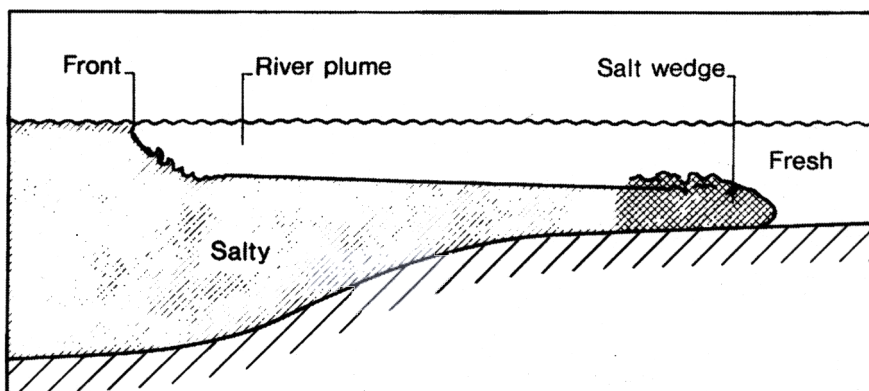


Figure 7.5 River plume and salt-wedge formation in an estuary.

Cross-sections of salt wedges have been measured on some river beds, such as those in the estuary of the Fisher River, which opens into the Strait of Georgia, USA (Geyer, 1983). Figure 7.6 shows how, using echo-sounding, the arrival of a salt wedge was recorded at a station near the coast. As the saline front moved past the station, it displayed a typical gravity current head.

The buoyant plume and dense wedge have been linked together in measurements made in the estuary of the small river Seiont at Caernarfon in North Wales by Simpson & Nunes (1981). The fresh-water discharge is forced back into the estuary during the flood tide, giving the appearance shown in figure 7.7. The tidal inflow comes from the right and passes beneath the river plume forming a front which is clearly marked by floating debris. A characteristic V shape appears in which two frontal arms meet at a point where rapid sinking motions occur.

A two-layer structure extends upstream of the front, along the axis of the river, with about 30 cm of fresh water overlying the intruding salt wedge. During the tidal cycle, after the time of maximum flood, the front starts to move downstream, maintaining the V configuration until the river widens and the front becomes convex. The front may be disrupted, but has a strong tendency to return to the same organised pattern.

Well-documented studies of fresh-water plume fronts have been made by Garvine & Monk (1974) for the Connecticut River, the largest in New England. This river has a high discharge of melt waters from mountains in the north, and in the spring approaches the salt-wedge regime. Figure 7.8 shows an aerial view of the frontal boundary of the Connecticut river plume in April. The river is on the right of the foam line, which sharply divides the yellowish-brown river water from the blue-green waters of Long Island Sound.

Measurements of the vertical density profile along a cross-section of the front are given in figure 7.9. This shows a gravity current of fresh water, which is about half a metre in depth.

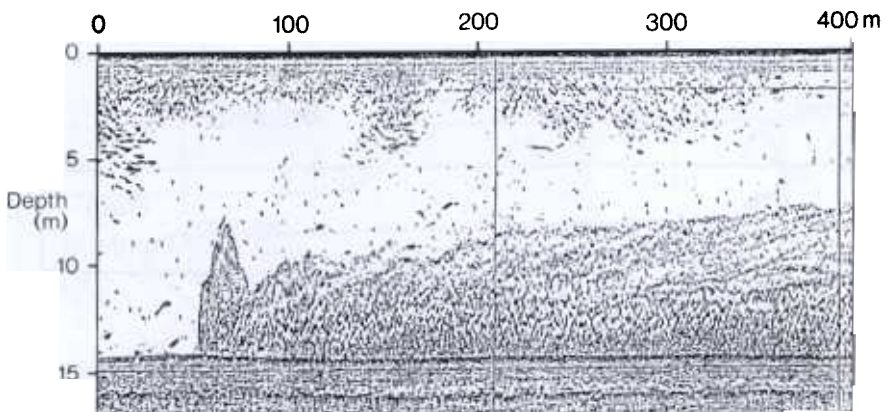


Figure 7.6 Salt wedge in the Fisher River, Georgia, USA detected by echo sounder. (Courtesy of David Farmer.)

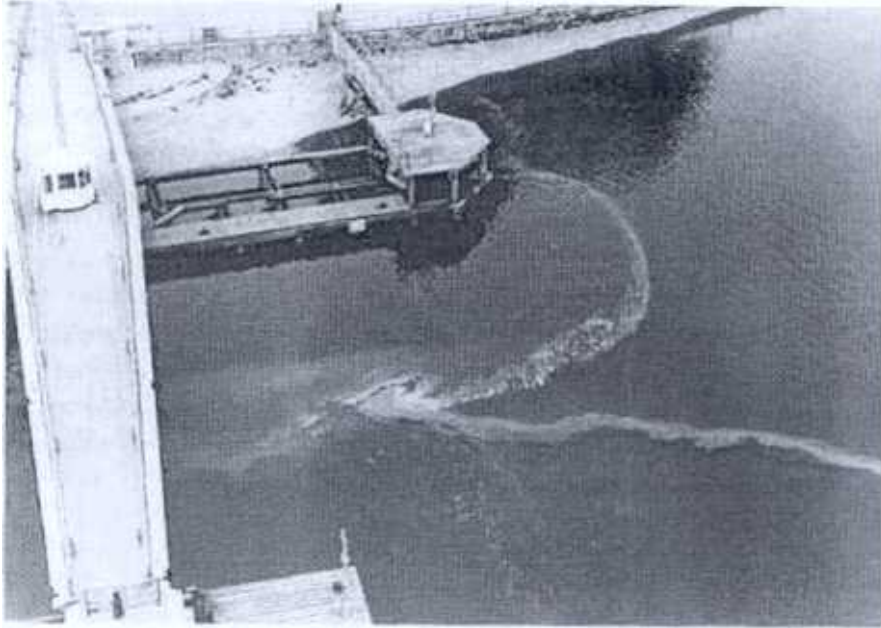


Figure 77 Tidal intrusion front in the Seiont River, Wales, outlined by floating debris. Saline strait water is moving from right to left beneath the fresh water of the estuary. (Courtesy of R. Nunes.)

Figure 78 Aerial view of the frontal boundary of the Connecticut River plume, 26 April 1972. River water is to the right. (Courtesy of R.W. Garvine.)



7.3 Fronts in fjords and lakes

Fjords, or sea-lochs, are deep inlets from the ocean influenced by the tides, the winds and fresh-water input from rivers. Many fjords have a very deep main basin, down to 1700 m, but most have a shallow sill at their mouth, of between 1 and 100 m high.

Several types of gravity current front have been observed in fjords (McClimans, 1978); figure 7.10 shows schematically some of the main processes which form them. Fjords with high river run-off have well-mixed layers of brackish water which can be as deep as 10 m. When the tide is high enough, a dense gravity current may flow over the sill into this brackish water and run down the slope into the fjord. After it has descended some distance it may have the same density as its surroundings; it then starts to move horizontally, forming an interflow or intrusion as shown in the diagram.

The formation of a deep unmixed layer is of practical importance in

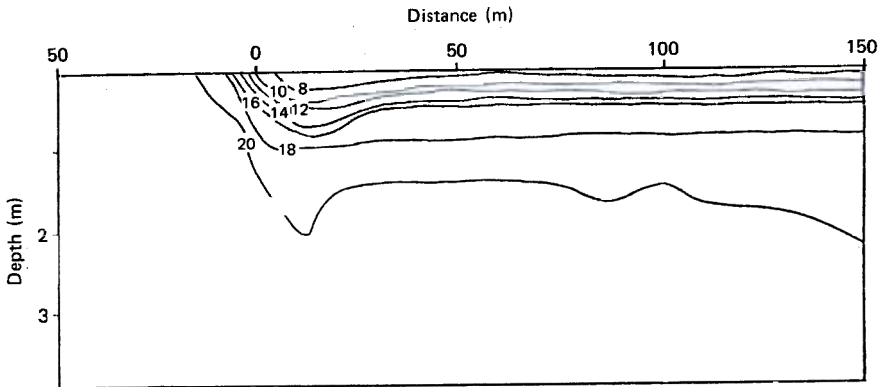


Figure 7.9 Density profile (in parts per thousand) normal to the colour front in the Connecticut River, 14 May 1973.

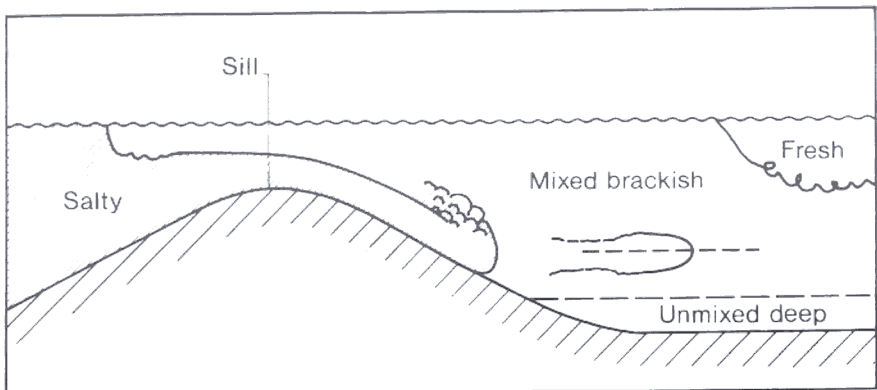


Figure 7.10 Some of the main processes which form gravity current fronts in a fjord.

connection with pollution, and deep water exchange determines the amount of available oxygen, which has important biological significance. The renewal of deep water due to the occasional flow of relatively dense water over the sill may occur only at rare intervals. For example, measurements in Loch Etive and in Loch Eil in Scotland by Edwards *et al.* (1980) have shown a replacement frequency of only about once per year, and that this is due to a gravity current process.

River fronts where extensive foam fronts are observed are permanent features of the surface waters of some fjords.

7.3.1 Lakes and reservoirs

A diagram of the flow of a river into a lake, or reservoir, is shown in figure 7.11. In this case the river carries suspended material and is therefore denser than the water in the lake; it may also be denser due to its low temperature. At the entrance to the lake, the dense river water descends along a clearly marked line called the 'plunge line'. This plunge line is the sign of a stationary front on the surface, between the two water masses. As in surface fronts described above, this front may be detectable from colour changes in the water and by floating material which does not descend in the downward flow at the front. As the river inflow descends the slope in the form of a gravity current, mixing takes place at the head and eventually the fluid may move horizontally as an intrusion or inter-flow.

7.4 Bores in the environment

Chapter 1 introduced bores and outlined some of the features that a bore has in common with the front of a gravity current. They both mark the leading edge of a continued process of mass transfer; this is not a typical feature of the behaviour of waves, the main effect of which is a transfer of energy.

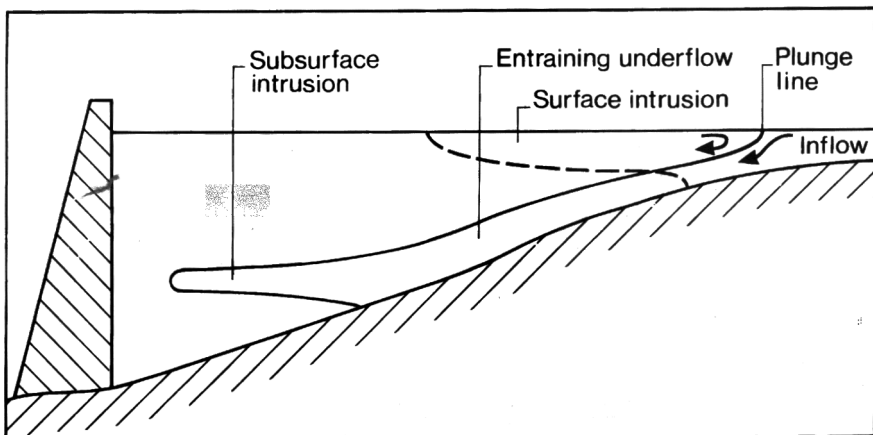


Figure 7.11 The flow of dense river water into a reservoir or lake.

Chapter 13 will examine the dynamics of bores and show how, at a comparatively weak bore, the loss of energy may be effected by a wave train, but that in a stronger bore there must be a turbulent mixing zone at the front. The latter process can be seen at the leading edge of a gravity current (except in very viscous flows), the leading edge being almost identical to that of an internal bore at an interface between two fluids.

7.4.1 Tidal bores in rivers

We showed a picture in Chapter 1 of the bore moving up the river Severn (figure 1.4). This is the best known bore in Britain, and is usually well developed at the spring tides at the spring and autumn equinoxes, when it can be as much as one metre high and may move up the river past Gloucester at speeds between 5 and 7 m s^{-1} (Rowbotham, 1964).

Whether a bore occurs in a river depends on the local conditions at the mouth; two of the most important requirements being a very high tide and a funnel-shaped estuary. Other important factors are the rate of flow of the river and the shape of the river bed (Tricker, 1964).

In Britain there are several other rivers which sometimes produce bores. After the Severn, the Trent usually produces the next most impressive bores. Here the tidal hydraulic jump is named the 'aegre' and the waves following it are called 'whelps' (Barnes, 1952). Clearly detectable tidal bores have been seen in several other rivers, although they may sometimes be only a few inches high.

Over 50 rivers throughout the world are known to have well-formed tidal bores (Bartsch-Winkler & Lynch, 1988). The best developed is probably the one in the Araguari River, on the coast of Brazil, which has been investigated by a team of scientists aboard the Cousteau Society vessel *Calypso*. The photograph in figure 7.12 shows this to be an undular bore, with over 20 waves clearly visible behind the front of the bore.

Some of the South American bores have only recently been explored, but in China one of the largest bores in the world has historical records going back over 2000 years. The Qiantang River in China, which enters the sea only 50 miles south of the Yangtse, has a bore with a legendary history going back to the fifth century BC. Already in the second century BC the Chinese understood its nature and expected a good bore at full moon.

As the city of Hangzhou grew up between the West Lake and the Qiantang River, its safety became more and more precarious and in 910 AD Governor Qian Liu built a dyke to meet the tide-water. He made bamboo bands, piled huge stones and drove in large trees. In addition he stationed hundreds of crossbowmen to shoot arrows, nominally 'to stay the forces of the tide', but perhaps more effectively as a public relations activity. An old print reproduced in figure 7.13 gives an impression of the scene as they began to build the wall, parts of which still stand today. The bore can be seen advancing as a turbulent line from the left.

Throughout the following thousand years the bore continued to trouble

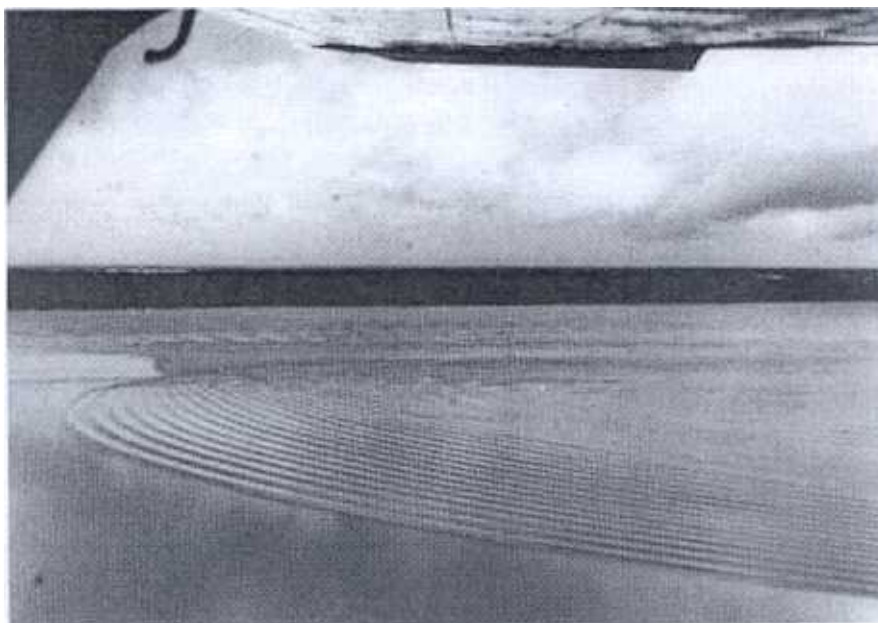


Figure 7.12 Tidal bore at the mouth of the Araguari River, in Brazil. The bore is undular, with over 20 waves visible. (Courtesy of D.K. Lynch.)



Figure 7.13 Protection against the bore in the Qiantang River: an historic scene.

the people of Hangzhou. It seems to have been somewhat variable in strength, since Marco Polo did not remark on it during his visit.

In the nineteenth century careful records were made by a British naval officer (Moore, 1888), who recorded bores of up to two metres in height. He noted how navigation was effected by the use of 'bore shelters'. These consisted of shelves half-way up the river wall, well above the water level, on which vessels were perched until the bore arrived and floated them off.

Although work had been done on maintaining the walls and digging out the channels, severe bores still sometimes occurred less than 20 years ago, in the Qiantang River. An example is shown of one of these in figure 7.14. In these views a special feature is the dangerous intensification which can occur as the result of reflection of a bore which strikes the wall at an angle. The turbulent bore

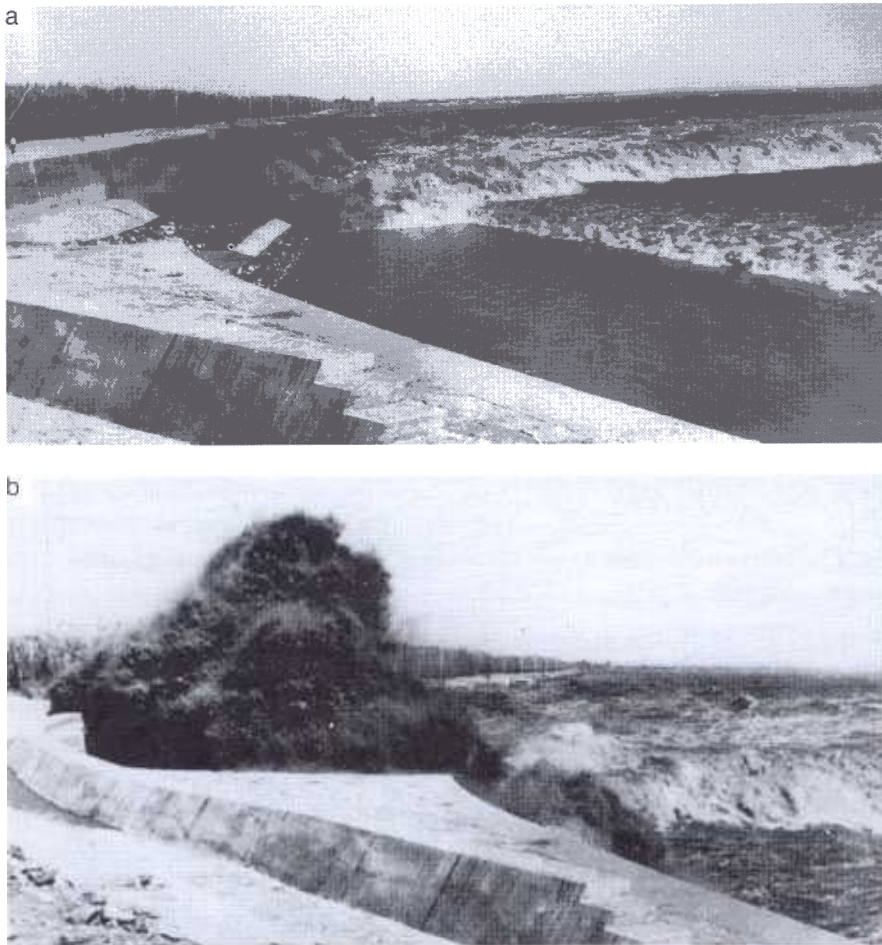


Figure 7.14 Intensification of a bore by reflection. In (a) the Qiantang bore in China has been reflected from the wall seen to the left. In (b) the original and reflected flow meet at the bend in the wall. (Courtesy of Zhejiang Provincial Estuarine Research Institute.)

approaches from the top right-hand side and is reflected from the wall on the left. After reflection the height of the bore is doubled and it strikes the obstacles in the foreground with great force. Work carried out by the Zhejiang Provincial Estuarine Research Institute has reduced the effects of the bore; this has been done by deepening the river channels.

The highest tides in the world occur in the Bay of Fundy in Canada and, as might be expected, some well-known river bores are associated with them (Dalton, 1951). One of these rivers, the Petitcodiac, has a very impressive bore which may be seen to best advantage from the riverside park provided for this purpose in the city of Moncton, New Brunswick.

7.5 Internal bores

There is good evidence for the existence of internal bores in rivers, lakes, fjords and the oceans. Echo-sounders can display the bore profiles and detailed measurements have been made using sensors of temperature, salinity and velocity.

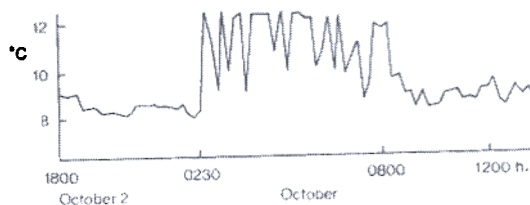
These bores are usually generated in a comparatively thin layer of water which lies above a deeper denser layer, so the front of the bore would be expected to appear as a wave of depression. Several different mechanisms have been established for the formation of internal bores in these commonly existing stratified layers.

7.5.1 Surges in stratified lakes

Internal bores have been observed in Loch Ness, which is 35 km long, about 2 km wide and 200 m deep (Thorpe *et al.*, 1972). The bores propagate in undular form at speeds up to 0.2 m s^{-1} towards the north west. They are often 10 m deep, with a series of waves to the same depth, about 10 km long.

The form of the bore is best shown in temperature measurements, as in figure 7.15. This record was made from a moored boat from which a probe was suspended at a depth of 40 m near the centre of the loch. The increase in temperature as the front of the bore passed shows that the isotherms were lowered and that the bore was a wave of depression. The change in level of the isotherms was about 12 m and the mean speed of propagation of the bore was found to be 0.37 m s^{-1} . It is believed that this bore is forced by wind-stress causing flow of near-surface water to one end of the loch.

Figure 7.15 Temperature at 40 m depth in Loch Ness during the passage of internal bore. (After Thorpe *et al.*, 1972.)



Even larger undular bores have been measured in Seneca Lake, New York by Hunkins & Fliegel (1973), where the isotherms are often 20 m deeper behind the front of the bore, which travels at 0.35 to 0.40 m s⁻¹.

7.5.2 Internal tidal bores in the ocean

Internal bores have been investigated off the coast of California by Cairns (1967). During the summer months, when a strong seasonal thermocline exists, the thermal structure approximates a two-layer system. It was found that as an internal tide moved inland its wave profile became increasingly asymmetric as the wave entered shoaling coasting waters. This asymmetry became more pronounced with increasing wave height and resulted in the formation of an internal tidal bore.

In other measurements made at La Jolla, California (Winant, 1974) similar surges of cold water were recorded. Since the surge was evident even on the bottom it was believed to be due to the run-up of broken internal waves.

7.5.3 Flows over sills or through contractions

The presence of a sill near the mouth of a river or fjord may be responsible for the formation of an internal bore at certain times during the tidal cycle. In many cases a response to tidal flow over a submarine sill is an internal hydraulic jump downstream of the sill (Gargett, 1980). Such a flow occurs in Knight Inlet, British Columbia, on the turn to flood tide when an undular bore emerges from the region of the sill. Figure 7.16 shows a record from a 200 kHz hull-mounted echosounder, taken as the ship traversed the bore. The leading edge of the undular bore is to the left of the picture and typical wavelengths are of the order of 100–200 m near the leading edge. At this internal jump the height ratio, or strength, is about 2.

Undular bores form at certain tidal stages in the two-layer flow through the Straits of Gibraltar (Farmer & Armi, 1986). Since in the Mediterranean, the effect of evaporation exceeds that of river discharge, the water is more saline than that of the Atlantic. As the tide rises, a layer of less-saline water flowing above a sill in the Strait enters the Mediterranean as an internal bore. The satellite photograph

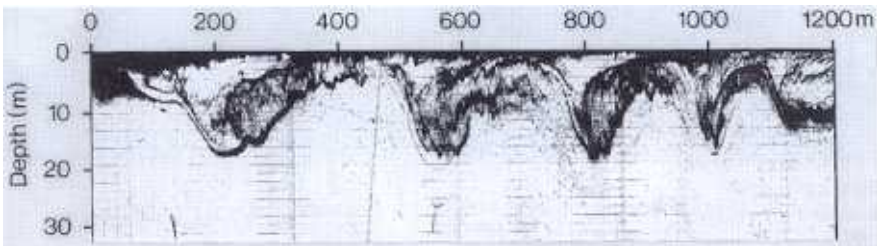


Figure 7.16 Echo-sounder record of an undular internal bore in Knight Inlet, British Columbia. (Courtesy of David Farmer.)

in figure 7.17 shows interfacial features associated with internal flow glinting in the sun and marks clearly the front of the internal undular bore spreading to the right into the Mediterranean.

7.5.4 Generation of internal bores by gravity currents

A number of observations have been described which are consistent with the generation by gravity currents of internal bores near water surfaces. Unfortunately, many of these are not well documented.

Developing sets of lines at the surface suggesting an undular bore have been recorded on several occasions. Some of these have appeared as foamlines on the surface and others, from airborne thermal imagery, have shown periodic lines of variation of surface temperature.

Figures 7.7 and 7.8 have shown how the convergence zone at the front of a gravity current of less-dense fluid can cause a single sharp line of floating foam and debris. Laboratory experiments can reproduce the early stages in the formation of a bore at the front of a gravity current. As the front of the bore moves along the surface of the water ahead of the leading edge of the gravity current it will develop its own separate foam line. This process will be repeated until a series of parallel foam lines is formed. Figure 7.18 is a photograph of a regular series of foam lines in Trondheim Fjord, Norway (McClimans, 1978), which is thought to have this explanation.

A similar pattern, suggesting an internal bore, has also been found in fresh-water river discharges into the sea. Cold fresh water from the Quinault River discharging into the NE Pacific shows a series of lines which have been shown to be successive boundaries of warm coastal-ocean water (Gross, 1972).

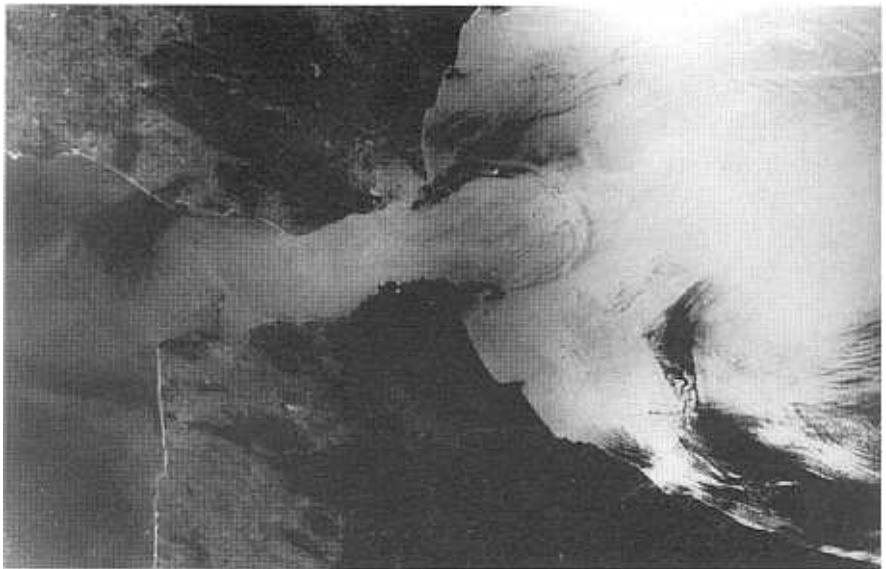


Figure 7.17 An undular bore formed by tidal flow through the Straits of Gibraltar. (Satellite photograph, courtesy of NASA).

7.6 Turbidity currents on the ocean bed

The deep ocean floor is sometimes violently disturbed by turbidity currents moving down from the continental shelf. The attention of oceanographers was first drawn to this fact by breaks in submarine telephone cables, but the suggestion that turbidity currents were responsible for these breaks and other phenomena such as submarine canyons formerly created much controversy.

Some enormous submarine 'landslides' are known to have set up turbidity currents at the edge of the continental shelf. The volume of sediment deposited by the well-studied turbidity current off the Grand Banks near Newfoundland in 1929 has been estimated to be as much as 100 km^3 . This is a thousand times the volume of the greatest landslide recorded on land. The events started with a severe earthquake which immediately broke a large number of submarine cables near its epicentre on the continental shelf just south of Newfoundland. But none of the numerous cables crossing the continental shelf in the area further south were affected. Further downstream from the epicentre, however, another cable broke an hour later. Then four other cables broke in succession, each in two or three places, the last break occurring 13 hours later and 300 miles distant. The details are shown in figure 7.19.

Submarine canyons are found in many sections of the continental slope. They are similar to river gorges on earth, with equally steep sides and depths. Turbidity currents have been observed actually flowing down some of these

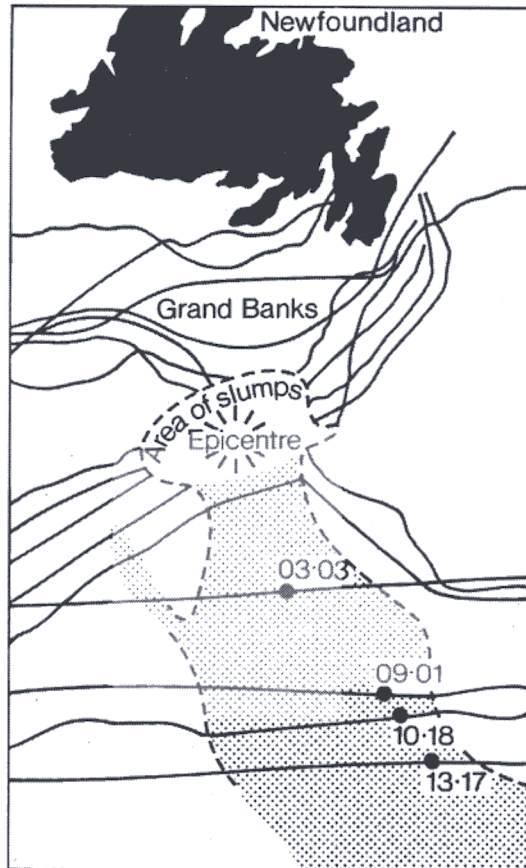


Figure 7.18 A regular series of foam lines seen in Trondheim Fjord. (Courtesy of the Norwegian Hydrotechnical Laboratory.)

canyons. A good example is the event in 1935 at the mouth of the Rio Magdalena in Colombia, when 450 m of a breakwater suddenly disappeared into the sea, and the same night a submarine cable was broken at a point 24 km out to sea and 1.5 km deep in one of the canyons which extend out to sea from near the river mouth. During repairs the cable was found to have grass wrapped round it of the type growing near the breakwater, suggesting that the slump had developed into a turbidity current capable of producing this long-distance transport. In this district, during the first 25 years since one of the cables was laid it has been broken by turbidity currents on 17 occasions.

Abyssal plains occur in many oceans; for example, they cover 10% of the floor of the North Atlantic, deviating from smoothness by only a few metres. Echo-soundings show, however, that the smooth plains are themselves underlain by a rugged base. Analysis of cores from these plains shows that they consist of sand and silt layers which appear to have come from the continental shelf, and that transport by turbidity currents is the most likely explanation.

Figure 7.19 Submarine cables broken by a turbidity current from the Grand Banks sediment slide, 1929 (marked by the dotted area).



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