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GRAVITY CURRENTS IN THE LABORATORY, ATMOSPHERE, AND OCEAN

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INTRODUCTION

A gravity current, or "density current," is the flow of one fluid within another caused by the density difference between the fluids. The difference in specific weight that provides the driving force may be due to dissolved or suspended material or to temperature differences. Gravity currents are primarily horizontal, occurring as either top or bottom boundary currents, or as intrusions at some intermediate level. The fluids are usually miscible and the mixing that results can play an important part in the dynamics of the flow. Since gravity currents are formed in many different natural situations and may also be man-made, knowledge of their properties is of importance in many scientific disciplines.

In the atmosphere, thunderstorm outflows and sea-breeze fronts are gravity currents of relatively cold dense air. Atmospheric-suspension gravity currents include avalanches of airborne snow particles, also fiery avalanches and base surges formed from gases and solids issuing from volcanic eruptions.

Gravity currents have important applications in aircraft safety, atmospheric pollution, entomology and pest control, and especially in dense-gas technology. Industrial accidents in which gravity currents may be formed include the spread of a dense gas from an accidental release.

In the ocean, gravity currents are driven by salinity and temperature inhomogeneities, or as turbidity currents whose density derives from suspended mud or silt. Lines of foam and debris on the ocean surface may indicate the front of a gravity current, frequently brought about by tidal processes. The latter also affect the behavior of gravity currents such as river plumes at the surface and salt wedges on a river bed. The important problems related to oil spillage on the sea have been the subject of a review paper in this series (Hoult 1972).

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In all the gravity currents
rotation is neglected.

THE HEAD OF THE CURRENT

At the leading edge of a gravity current there is a characteristic "head," deeper than the following flow. This is a zone of breaking waves and intense mixing and plays an important part in the behavior of the current. In a gravity current flowing horizontally this head remains quasi-steady, and is about twice as deep as the following flow, but in a current flowing down a slope the size of the head continually increases. A current flowing along a horizontal surface usually has a "nose," or foremost point, raised a short distance above the ground.

A "universal profile" of a gravity current head does not exist, as even for flows into calm surroundings the value of the excess head height above the following flow varies with the fraction of the total depth occupied by the current. The form of the head is strongly modified by opposing and following ambient flows, and other physical effects.

Some early experimental work on gravity currents was carried out by Schmidt (1911), who used a laboratory water channel to model the front of an advancing cold squall in the atmosphere. The silhouettes of some of his gravity-current heads are still worth viewing and are shown in Figure 1. In Schmidt's shadow-pictures the views (*a*) and (*b*) are of flows with low Reynolds number, Uh/ν less than 100. (U is the velocity of the front, h the depth of the current, and ν the kinematic viscosity.) As the temperature difference, and hence the Reynolds number of the flow, increases, the shape of the head of the gravity current alters, the foremost point of the nose approaches the ground, and more intense mixing occurs at the front and top of the head. The final view (*f*) shows a profile typical of

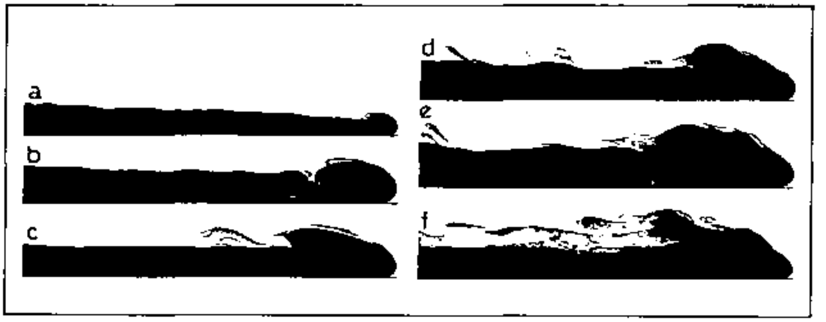

Figure 1 Profiles of the head of a gravity current in a laboratory tank (from Schmidt 1911). The temperature difference increases from a very small value in (*a*) to 35° in (*f*).

flows with Re greater than 1000 in which billows are seen streaming back from the upper surface of the gravity-current head.

Billows

In most cases the billows formed on the upper surface are broken up in a complex three-dimensional flow but slit-lighting reveals Kelvin-Helmholz instabilities (Simpson 1969). Winant & Bratkovich (1977) measured the fluxes in and out of the frontal zone of a gravity current from a carriage moving with the front. They found the mass flux of heavy liquid into the front to be of order 0.15 Q, where Q is the mass flux per unit width of the current. Simpson & Britter (1979a), holding a front stationary in a water channel, also found the ratio of the mean overtaking speed U_o to front speed U_f to be equal to 0.15.

Lobes and Clefts

At the head of a gravity current moving along a horizontal surface there is a complicated shifting pattern of lobes and clefts, believed to be caused by gravitational instability of the less dense fluid which is overrun by the nose of the current (Simpson 1972a). A rough estimate of the expected flux of light fluid into the head by entrainment of about 0.2 Q was made by Allen (1971), and measurements using dye lines ahead of the front give 0.13 Q as a probable upper limit (B. R. Morton and J. E. Simpson, unpublished).

THE DYNAMICS OF GRAVITY-CURRENT FRONTS

The interface between the two fluids at the head of a gravity current is a typical frontal zone, that is, a region in which, although there is intense motion and mixing, a high density gradient is maintained.

The motion of a gravity current has been described in terms only of the depth and density difference at the head itself by Keulegan (1957). He found from extensive measurements of the advance of saline currents along a horizontal floor into calm fresh water that the velocity $U = 1.05$ $(g'h)^{1/2}$, where $g' = g\Delta\rho/\rho$ and h is the depth of the following steady flow. These results were mainly obtained from flows occupying about 1/5 of the total depth H, but more recent work on gravity currents from a lock at the end of a water channel has shown that U is sensitive to changes in the value of h/H in the range 1/3 to 1/10 (Simpson & Britter 1979a).

Inviscid-Fluid Theory

Benjamin (1968) applied inviscid-fluid theory to study aspects of a steady gravity current; in particular, he showed the essential role of wave-breaking and the associated energy losses. He analyzed the front of a frictionless two-dimensional gravity current in terms of a "cavity flow" displacing a fluid beneath it (see Figure 2*a*.) In a closed channel, with axes moving with the front of the current, continuity and Bernoulli's equation applied along the interface give two equations involving the velocity and depth h_2 of the flowing layer. Being frictionless the "flow force" (total pressure force plus the momentum flux per unit span) is also conserved, resulting in a solution $h_2 = 1/2H$. Thus the only steady energy-conserving flow (implied by the use of Bernoulli's equation) is one in which the advancing layer fills half the channel. Flows in which $h > 1/2H$ are not possible, and if $h < 1/2H$, as is found in most practical situations, the loss of energy at the front exceeds that available by wave radiation so that "breaking" must occur.

Benjamin also showed the importance of the fractional depth $h/H = \phi$, say. The Froude number, $U/(g'h)^{1/2}$, based on the velocity U of the front, is $2^{-1/2}$ at $\phi = \frac{1}{2}$, equals about 1 at $\phi = 1/5$, increasing to $2^{1/2}$ as $\phi \rightarrow 0$. In Benjamin's treatment of the velocity of the head under "deep" water (i.e. $\phi \rightarrow 0$) if the pressure downstream in the wake is taken to be hydrostatic so the dynamic pressure $1/2\rho U^2$ at the stagnation point 0 equals the difference between the hydrostatic pressure at the boundary far upstream and downstream, it follows that

$$\tfrac{1}{2}\rho U^2 = g(\rho_1 - \rho_2)h$$

$$\text{or } U = 2^{1/2}(g'h)^{1/2} .$$

The same result had been obtained by von Kármán (1940) by applying the Bernoulli condition along the interface, but this is invalid in deep water since the interface must be dissipative. Prandtl (1952) deduced a front velocity half that of the layer behind, but his argument applies only to the initial transient phase of the motion.

Benjamin also calculated the approximate shape of the interface. The slope at the stagnation point on the ground is 60°, a result previously deduced by von Kármán.

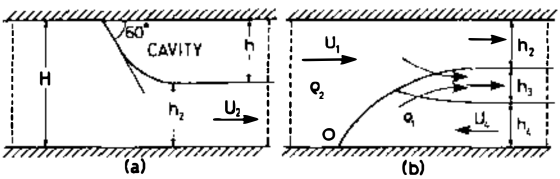

Figure 2 Theoretical treatment of a gravity-current front, with flow relative to the front. (*a*) Benjamin (1968); (*b*) Britter & Simpson (1978).

An Inviscid Current with Mixing

As a first step towards realistic gravity currents, in a semiempirical analysis by Britter & Simpson (1978), the flow relative to the gravity-current head is divided into three regions, as in Figure 2*b*. The bottom region is the flow into the gravity-current head of dense unmixed fluid, depth h_4. The top region contains only the less dense fluid, depth h_2. Between the two is a mixing region, whose depth h_3 is that of the wake of the collapsed billows. This region has nonuniform velocity and concentration profiles determined by experiment. Values of the Froude number $U/(g'h_4)^{1/2}$ were calculated using continuity and momentum equations and Bernoulli's equation applied along the floor to the foremost stagnation point *O*. This Froude number varied both with the fractional depth h_4/h_1 and also with $q = g'Q/U^3$, the nondimensional mixing rate. Values of q needed to close the equations could either be measured experimentally or else deduced from billow properties.

The mixing rate and billow properties were studied using a water channel with a moving floor. A front with no friction at the floor was modeled by holding it stationary on a fixed floor just downstream of the end of the conveyor-belt section. No fluid was overrun at the nose, hence the lobe and cleft structure was absent and the mixing billows above the head were nearly two-dimensional. The difference between the flow observed and the familiar arrested saline wedge (Riddell 1970) appears to be in the imposed velocity profile which has a critical effect on the mixing (see Figure 3). The nondimensional breakdown size of the billows, $R_L = g'h_3/(\Delta U)^2$, where ΔU is the velocity difference across the front, was found to be 0.33, close to that obtained by Thorpe (1973) for billows forming at an interface with very small initial Richardson number. The Froude number was about 1 for fractional depth h_4/h_1 about one fifth of the total depth. For smaller fractional depths, down to about 0.05, the value of the Froude number rose to approximately 2.

These results appear to model closely the behavior of a gravity current of fresh water moving along the free surface above saline surroundings,

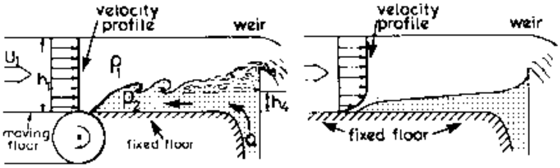

Figure 3 (*a*) An inviscid gravity current on a fixed floor downstream of a moving flow and floor. (*b*) An "arrested saline wedge" on a fixed floor, brought to rest by an opposing flow.

a situation of interest at much larger scales. Modeling such flows in the laboratory by small-scale currents along a free surface is difficult because it is hard to protect the free surface from contaminants that can modify the flow.

Front Advancing over a Horizontal Surface

In the next step, including friction on the boundary, the main difference from the inviscid model can be related to the height above the ground of the mean position of the foremost point of the head. This is considered as a stagnation point, and for large values of Re, both laboratory and atmospheric observations suggest a constant value for the nose height of about 1/8 of the total height of the gravity-current head (Simpson & Britter 1979a). An alternative approach, used by Kranenberg (1978), is to include an empirical head-loss coefficient for the stagnation streamline.

Head- and tail-flow effects on the front of a gravity current moving along a horizontal surface have been examined in a water channel with a moving floor by Simpson & Britter (1980). Head flows, or "head winds," are simulated by bringing the front to rest on the moving floor with an opposing flow at a greater speed than that of the floor. Tail winds are obtained by moving the floor faster than the opposing flow. With a head wind the head profile is longer and the nose height lower than in the familiar calm case. With a tail wind the head is shorter and the nose height is larger. A head or tail wind is found to change the speed along the ground by 3/5 of the applied wind.

Values of the overtaking speed relative to the front, U_4, were compared with U_1, the flow relative to the front and the values of U_4/U_1 were all found to be close to 0.15, independent of the values of the head or tail flows.

The value of $R_L = g'h_3/(\Delta U)^2$ was deduced to be 0.5, in all head and tail wind cases. This is greater than the value measured in the two-dimensional (inviscid) case, but close to that already found in the calm case along a horizontal floor, so it seems that the shape of the head and mixed region adjusts to maintain this approximately constant layer Richardson number.

Gravity Currents on Slopes

Georgeson (1942) made direct measurements of the advance of a quantity of methane along the roof of a passage in a mine. From these and later experiments, e.g. Wood (1965), Middleton (1966), Hopfinger & Tochon-Danguy (1977), it is clear that the motion of a gravity current down an incline is appreciably different from that on a horizontal surface. On slopes from a few degrees to 90°, for a given buoyancy flux, there is a nearly constant front velocity that is only about 60% of the mean velocity of the following flow. The head volume increases, both by direct entrainment and by addition from the following flow. There is little variation in front speed with slope, because although the gravitational force increases, so does the entrainment, both into the head and into the flow behind it. Direct entrainment increases with slope, leading to 1/10 of the head-growth at 10° and about 2/3 at 90°. With a steady buoyancy flux Q, Britter & Linden (1980) found a constant head velocity for slopes greater than 1/2°, and from 5° to 90° the front velocity was given by $U/(g'Q)^{1/3} = 1.5 \pm 0.2$.

The release of a finite quantity of dense fluid down a slope has practical applications and the resulting "inclined thermals" have been investigated by Beghin, Hopfinger & Britter (1981).

THE SPREAD OF NEGATIVELY BUOYANT FLUID

Release of a Fixed Quantity of Fluid

When a fixed volume of fluid is released into nonturbulent surroundings it spreads with a very little mixing except near the leading edge which advances at a velocity dependent on local parameters. However, a relationship between the current depth and the frontal speed is only part of the solution of the important practical problem of finding the rate of advance of a gravity current.

Fay (1969) determined the rate of advance in terms of the balance between the horizontal buoyancy forces and the inertia forces in the current. For the axisymmetric case, he found

$$R \sim (g'q)^{1/4}t^{1/2}$$

where R is the radial coordinate of the front of the current and q is the volume. With a fixed volume the current eventually becomes thin enough for viscous forces to take over from inertia forces to give the balance

$$R \sim (g'q^2\nu^{-1/2})^{1/6}t^{1/4} \, ,$$

where ν is the kinematic viscosity. These two equations give a transition time $t_* = (q/\nu g')^{1/3}$. Fay identified a third stage of the spreading for oil-water flows when there is a balance between viscous forces and surface tension.

On the grounds that the length of the current greatly exceeds its vertical thickness, Hoult (1972) based his analysis on the depth-averaged shallow-water equations. Retaining only the buoyancy and inertia terms, he solved the equations and evaluated the coefficients from experiments on the spreading of oil over water. Hoult obtained

$$R = 1.3\,(g'q)^{1/4}t^{1/2} \text{ (axisymmetric)},$$

$$L = 1.6\,(g'q)^{1/3}t^{2/3} \text{ (two-dimensional)} .$$

The spreading laws when viscosity dominates inertia were obtained by Hoult as

$$R = 0.94\ (g'q^4/\nu)^{1/12}t^{1/4}\ \text{(axisymmetric)}\ ,$$

$$L = 1.5\ (g'^2q^4/\nu)^{1/8}t^{3/8}\ \text{(two-dimensional)}\ .$$

Lock-Exchange Experiments

Since the pioneering experiments of O'Brien & Cherno (1934) many gravity currents have been released from behind lock-gates. However, most of these flows start with a constant-speed regime, showing very little agreement with the above power laws. One difference from Hoult's experiments is that in all these experiments the dense fluid released was originally the same depth as the fluid in the rest of the channel. When the partition was removed the initial flow pattern was identical to that of "Mutual Intrusion" experiments in which the partition is at the center of the tank. In such flows Yih (1980) showed from energy considerations that $U = \frac{1}{2}(g'H)^{1/2}$. Using much larger tanks, Barr (1967) found the constant speeds of the fronts were 0.47 $(g'H)^{1/2}$ along the ground and 0.58 $(g'H)^{1/2}$ at the free surface, until a viscous regime was reached.

Huppert & Simpson (1980) showed that if steady-flow results relating the head Froude number and the fractional depth of the gravity current were assumed to apply in a simple box model, then an almost constant velocity regime was to be expected in the early stages of a finite volume release. They called this the "slumping" regime and showed that most of Keulegan's 1957 experiments moved directly from this regime to a viscous one. The constant speed came to an end when the fractional depth had fallen to about one tenth, in their two-dimensional and axisymmetric experiments.

REFLECTION EFFECTS IN LOCK-EXCHANGE GRAVITY CURRENTS As the result of further experimental work an explanation can be given of the end of the constant-speed regime. When dense fluid is released into a channel from a lock of finite length the reverse upper flow is reflected from the rear wall of the lock as a depression behind the underflow, which then becomes a slug of fluid with only a thin layer of dense fluid following it (Keulegan 1957, Barr 1967). The head of this slug moves at nearly constant speed but its length decreases as it is eroded from the leading edge (see Figure 4). After the front has traveled about ten lock-lengths the reflection has almost reached the head, the slug form disappears, and the head is followed by a layer about one tenth of the total depth of the fluid. It now advances with distance L proportional to $t^{2/3}$, as described by inertia-buoyancy theory. This regime, which may be short or even nonexistent, is followed by a viscous-buoyancy regime in which L varies with $t^{3/8}$.

Replotting Barr's data, suitably nondimensionalised, for flows influenced by reflection confirms ten lock-lengths as the extent of the constant-velocity regime in currents along the ground. In his experiments on free-surface gravity currents the reflections appear to influence the head after traveling about twenty lock-lengths.

Axisymmetric gravity currents from finite locks also have a short constant-velocity regime, which ends when the reflection approaches the front after about four lock-lengths. In the collapse from a very short lock the reflection causes a concentration of mass in a narrow head annulus when this stage is reached.

Constant Buoyancy Flux

Consider a gravity current formed by a steady buoyancy flux either at a free surface or along the ground, first in a parallel-sided channel. An

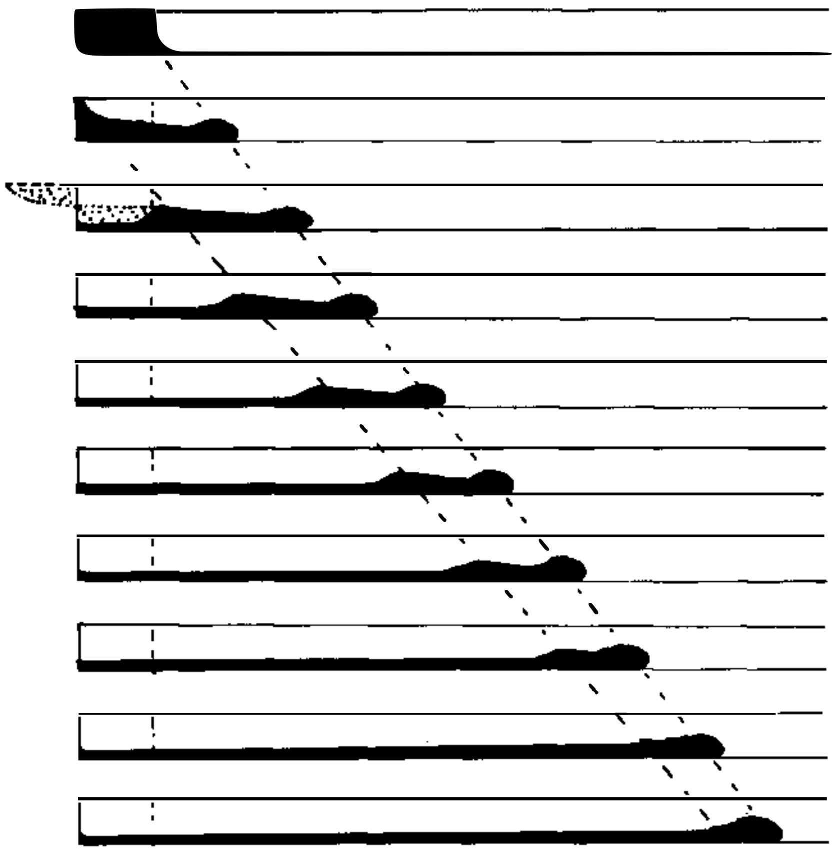

Figure 4 Development of the reflected upper current in a lock-exchange flow.

example is the warm outflow from a power station, where both the advance of the initial leading edge and the mixing during later stages are of interest.

These "starting plumes" are different from the lock-exchange flows we have considered, in which a barrier is removed in a tank containing fluids of different density on either side. In lock-exchange flows there is no total flow across any cross section of the tank, so a gravity current of large fractional depth will have a faster return current above it than will a starting plume of the same depth.

Wilkinson & Wood (1972) showed that for inviscid, non-mixing starting flows the Froude number $= [(2 - \phi)/(1 - \phi^2)]^{1/2}$ (ϕ is the fractional depth h/H of the current). This expression varies much less with ϕ than the corresponding one for lock-exchange flows $[(2 - \phi)(1 - \phi)/(1 + \phi)]^{1/2}$.

It is possible to set up a flow rate in which the layer stays uniform for some distance along the flume (Barr 1959), but for increasing distances the velocity decreases and the layer thickens. Lean & Whillock (1965) concluded that for an inlet Froude number greater than 1 there exists an entraining hydraulic jump at the interface, and it seems that the rate of entrainment here and the conditions downstream are controlled by the gravity-current head.

The analysis of Wood (1967) was similar to that for a hydraulic jump in which the amount of mixing depends on the turbulence and hence on the inflow Froude number. Wilkinson & Wood (1971) examined the characteristics of the hydraulic jump associated with some form of downstream control in a two-layer system and showed that this "density jump" is able to entrain the varying amounts of ambient fluid necessary to satisfy a range of downstream controls. However, along a horizontal floor with a gravity-current head as control no equilibrium state exists (Koh 1971), and the velocity of the flow continues to fall and eventually causes the density jump to flood.

AXISYMMETRIC FLOWS Analogous results to the two-dimensional flow have been obtained for axisymmetric flows, of interest in describing a spreading plume of sewage, or of cooling water from a power station.

The analysis of Chen & List (1976) described the spread of such a plume in separate regimes, first dominated by an inertia-buoyancy force balance and then by a friction-buoyancy balance. The rate of spreading in the first regime was shown to be $R(t) = k_1 (Qg')^{1/4}t^{3/4}$, where $k_1 =$ 0.75 and Q is the mass flow per unit width. The changeover from inertia-buoyancy balance will occur on the viscous time scale $t_* = (Q/\nu g')^{1/2}$ and the form of the viscous-buoyancy solution is $R = k_2(Q^3g'/\nu)^{1/3}t^{1/2}$. Recent experiments by Britter (1979) gave a value for $k_1 = 0.84$ and for $k_2 = 0.67$.

The spread of a gravity current from a continuous source into a stratified cross-flow has been investigated by Jirka (1980). He determined the shape and velocity distribution enclosing the source, including the length of the upstream intrusion. His laboratory observations agree with the analysis for small enough values of the near-field momentum, in which the radially expanding jet is not entraining.

Flow at Very Low Reynolds Number

At the onset of the "viscous-buoyancy" regime discussed above, the Reynolds number based on the total head height, $\mathrm{Re} = Uh/\nu$, is about 500. The raised head disappears when $\mathrm{Re} \simeq 10$. At lower Re, in flows along a rigid boundary, cells of overrun fluid may not rise through the dense fluid, but can remain in a "rice-grain"–like pattern on the floor. In such flows through an unstable layer, interaction between the gravity-current front and thermals appears to be possible (Simpson 1972b).

Gravity currents at low Re occur naturally in some geological events. For example, H. E. Huppert (unpublished work) has had some success in the use of laboratory gravity-current models to explain observations of the flow of lava in the crater at the top of Soufriere, St. Vincent.

The Spread and Dilution of Heavy Gas Cloud

Notable safety hazards can arise from the accidental release of a large quantity of negatively buoyant gas that is combustible or toxic. After an almost instantaneous release of vapor a drifting cloud is formed, with diameter greater than its thickness, and it is important to know both the rate of advance of the cloud and its dilution.

A recent paper by Fay (1980) compares various models proposed for treating the dispersion of dense gas clouds. These are mostly based on the box model which considers the cloud to occupy initially a cylindrical box of radius R and height H. R increases with time, with radial speed proportional to excess hydrostatic height and $dR/dt = a\,(g'H)^{1/2}$. Some field tests and water-tank and wind-tunnel measurements are compared with model predictions.

Nearly all recent models of dense-cloud behavior have included major gravity-current effects and many different criteria have been proposed for separating the early stage when gravity currents dominate the mixing process from the later stages when atmospheric turbulence dominates (McQuaid 1979).

AMBIENT TURBULENCE Most of the mixing in a gravity current occurs in the region of the head and a stable layer is laid down above the following current. When the ambient level of turbulence is small it can have only a small effect on the mixing of the dense fluid; however, if we consider the spread of a finite amount of dense fluid into a turbulent environment, although at the start gravity current forces dominate, as the cloud thins and the velocity of the front is much reduced, the effect of external turbulence on the mixing can become appreciable. In the simple model of a gas cloud by van Ulden (1974) this transition was taken to occur when U_f, the speed of the front, became less than u_*, the friction velocity. Van Ulden argued that at this point the cloud, whose height had been decreasing, began to increase again.

TURBULENCE EXPERIMENTS N. H. Thomas and J. E. Simpson (unpublished) have used an oscillating grid to maintain and enhance the shear turbulence in a streaming flow over a stationary gravity current. In this way they were able to impose turbulent intensities u'/U_f at any level from zero (the "standard" gravity current) up to about ten or more (as may be found in tidal flows).

At these large intensities the frontal zone appears as a wedge, with a fluctuating sharp, well-defined interface separating the undiluted current flow and the turbulent surroundings. The current, maintained by a continuous flow in at the rear, is eroded but not diffused. This picture is different from van Ulden's, in which the transition at $u'/U_f \geqslant 1$ is to upwards diffusion mixing of the current with its surroundings.

A conclusion from this work is that in the limit $u'/U_f \gg 1$, the mixing rate is independent of U_f, at least when the fractional depth is small, and that the entrainment speed (mixing flux per unit area) is scaled in accordance with Turner's (1968) result for the static two-layer system.

MATHEMATICAL MODELS A number of mathematical models have been developed using solutions of the equations of fluid motion to elucidate the behavior of a gravity-current head or the collapse of a cloud of dense gas. The models of Daly & Pracht (1968) and Vreugdenhil (1976) both employ the marker and cell method, but the latter included the hydrostatic approximation. Others, eddy viscosity models, have been offered by England & Teuscher (1978), Thorpe et al. (1980), Vasiliev et al. (1973), and Kao, Park & Pao (1977, 1978) but a detailed discussion of these models is beyond the scope of this review.

IN THE ATMOSPHERE

Thunderstorm Outflows

The downdraft section of a thunderstorm plays an important part in the structure and regeneration of severe storms (Thorpe et al. 1980). Good agreement between observations of the frontal properties of the cold dense outflow resulting from the downdraft suggests that laboratory gravity currents are reasonable analogue systems (Idso et al. 1972, Simpson & Britter 1980). For example, referring to the head- and tail-wind results described above, the laboratory results give the relationship $U_0/U_\Delta = 0.91 + 0.62\ U_2/U_\Delta$, where U_Δ is the densimetric velocity $(g'h_4)^{1/2}$, and U_2 is the external wind measured in the direction of advance of the front. Eighteen atmospheric observations from Miller & Betts (1977) and from Goff (1976), normalized in this way, gave a similar result.

Understanding the details of air flow near the front of this strong gravity current is important for safety of flight in large airplanes. Several accidents have been associated with flights through these small-scale fronts (Fujita & Byers 1977). Danger may occur through overstressing the aircraft by flying through vertical wind-shear, or through sudden large horizontal wind changes during takeoff or landing. For example, a case has been reported in which a wind discontinuity of 30 m s^{-1} lay across the runway (Fujita & Caracena 1977). The use of an acoustic sounder (Hall et al. 1976) has shown vertical wind-shears after the passage of a gravity current which were large enough to be hazardous to aircraft. Laboratory models give an estimate of similar value in the mixing zone after the breakdown of billows a few head-heights back from the leading edge.

A system has been installed in the neighborhood of Dulles Airport, Washington, D.C., to obtain warning of the arrival of such fronts, which often are invisible. A network of sensors is used to follow their progress by measuring the associated rapid change in pressure on the ground (Bedard et al. 1977).

Sea-Breeze Fronts

Sea breezes brought about by diurnal changes in air temperature over the land and sea are found at many of the world's coasts. The inland boundary of the sea breeze may often form a small cold front and detailed measurements from pilot balloons and instrumented aircraft in southern England show that in the late afternoon the behavior is similar to that of any other cold outflow or gravity current (Simpson, Mansfield & Milford 1977).

In Australia an extensive study of deeply penetrating sea-breeze fronts has been made by Clarke (1961, 1973). A mean speed of 3.5 m s^{-1} was measured, but fronts with onshore prevailing wind moved with speeds up to 7 m s^{-1}, traveling over 200 km from the coast. Many investigations of sea-breeze fronts have been motivated by pollution studies, and the sea-breeze circulation in some cases has been shown to recirculate pollutants emitted near a shoreline (Lyons & Keen 1976).

Airborne insects may follow similar flight paths near the coast, and Rainey (1963) has shown the importance in the life history of locusts of the convergent flow at small-scale fronts. Other pests, such as the spruce budworm moth in Canada, have been concentrated at sea-breeze fronts enabling airborne radar to clarify details of the sea-breeze frontal circulation (Schaefer 1979).

IN THE OCEAN

Conspicuous lines of foam or surface debris are often formed by surface convergence and such bands along the sea surface across which the density changes abruptly show a subsurface structure similar to that at atmospheric fronts. Such fronts in the ocean, known for many years to Japanese fishermen in their search for high concentrations of fish, were investigated scientifically by Uda (1938). Many fronts, especially those created by tidal processes, appear to be governed by simple gravity-current frontal dynamics.

Shelf-Sea Fronts

Shelf-sea fronts are induced at the transition between well-mixed and stratified water. Tidal currents in shallow seas cause high levels of turbulent dissipation which mix downward the seasonal buoyancy input and prevent stratification. The boundary between the mixed and stratified regions is often a well-defined front with a sharp change in surface temperature.

Such fronts have been studied on the European continental shelf. There are several regions where such fronts are regularly detected (J. H. Simpson et al. 1978, Pingree et al. 1974), and infrared satellite images have been tied up with observations from ships. These fronts have been shown to be nongeostrophic with flows of 2 to 16 cm s $^{-1}$ in the mean direction of the fronts.

River Plumes and Salt Wedges

When the river-discharge currents closely match the tidal currents in an estuary, a tidal intrusion front may form, together with the associated salt wedge (Officer 1976). Well-documented measurements of fresh-water plumes and plume fronts have been made by Garvine (1974) and Garvine & Monk (1977) in the Connecticut River. Their measurements at the front are consistent with the gravity-current model described above. For example, in one set of measurements the plume was about 100 cm deep at the front, with a mean density difference of 1.2% and moved at $U = 50$ cm s^{-1}, giving a Froude number $U/(g'h)^{1/2} = 1.5$.

Fronts in Fjords

Deep-water renewal in fjords depends on several processes, one of which is the gravity-current mechanism. With a shallow sill entrance to a fjord, inflows may be intermittent and at spring tide a salty flow may flow down the slope past the sill. Currents flowing down a slope of 6° in a Scottish fjord had a front speed about 50% of the speed of the following flow, as in laboratory measurements (Edwards & Edelsten 1977).

SUSPENSION FLOWS

Nearly all the treatment of saline gravity currents can be applied to suspension flows, if we bear in mind that at any particular time a vertical gradient of density is likely to exist (Middleton 1966).

Turbidity Currents

Under-water muddy slumps can change into turbidity currents with density difference due to suspended particles. It is believed that they transport materials from shallow to deep water, causing erosion of underwater canyons, the building of submarine fans along the foot of the continental rise, and sedimentation on abyssal plain. They are responsible for damage to submarine cables and for the formation of tsunamis. A critical history of investigations of turbidity currents has been given by Longinov (1971), and many aspects of their behavior have been studied by Komar (1972, 1977).

Branching channels seen on the surface of Mars resemble some of those on the ocean bed of Earth, carved out by turbidity currents, and it has been suggested that some of the Martian channels could have been formed by atmospheric-suspension gravity currents (Komar 1979).

Allen (1971) related the lobe and cleft structure observed at the head of saline flows via the transverse variation of bed-shear stresses to observed sedimentary structures. The longitudinal branching current ridges seen beneath sandstones attributed to turbidity-current deposition (Dzulyinski 1965) are examples.

One difference from the gravity currents previously examined is in the manner of starting and maintaining the necessary suspension of particles. Reviews of the processes of transformation of the gravitational movements of sediments into a sediment-carrying current were given by Pykhov & Longinov (1972) and Pykhov (1973).

Avalanches

An avalanche consisting of airborne snow particles is a spectacular example of a gravity current running down a slope. Voellmy (1955) described avalanche speeds between 50 and 120 m s^{-1}, with a density close to the ground between two and twenty times that of air. Observations conform with results from laboratory gravity-current studies, but caution needs to be taken in scaling flows with a large density ratio in which the Boussinesq approximation is hardly realistic. Conditions for the occurrence of avalanches have been reviewed by Shen & Roper (1970) and the problems of avalanche research summarized by de Quervain (1966).

Nuées Ardentes

Surges called *nuées ardentes* can originate from explosive volcanic eruptions as extremely hot, opaque, billowing clouds rushing down the side of the mountain. Examples have been filmed from airplanes (Moore & Melson 1969, Stith et al. 1977) showing speeds approaching 50 m s^{-1} over distances of several kilometers. Fluidization caused by gases released from the particles or entrained by lobes and clefts may play an important part in generating these high speeds (Wilson 1980). Reimers & Komar (1979) have pointed out that some of the morphological features associated with volcanoes on the planet Mars are similar to those on Earth formed by explosive volcanic gravity currents, and could have a similar origin.

Base Surges

Base surges are also suspension flows resulting from volcanic activity. These result from explosive volcanic eruptions into a watery environment, and unlike the nuées described above, are cool and moist and usually annular in form (Moore 1967).

AMBIENT STRATIFICATION

Gravity currents flowing through stratified surroundings may generate internal waves, and some interesting current-wave interactions have been observed. These are strongly dependent on the relative depth of the gravity current h and the depth H through which the ambient stratification extends (see Figure 5).

Sharp Interfaces

INTERMEDIATE CURRENTS After a section of two-layer fluid has been thoroughly mixed and released, a symmetric current flows along the interface. When the interface is sharp, breaking billows appear at the head, provided the Reynolds number is large enough (Simpson & Britter 1979b). The structure and dynamics of the resulting front are similar to an inviscid gravity current reflected about a horizontal plane.

BOUNDARY CURRENTS Holyer & Huppert (1980) dealt with steady flows in which waves are only swept downstream from the head and cannot go upstream. Simpson (1980) released a finite amount of dense fluid along the lower boundary and showed how the behavior of the current varied in relation to the speed of long waves on the interface between the two fluids.

A range existed in which a sudden change appeared at the gravity-current head as the flow changed from super- to subcritical. This was associated with an interfacial wave propagating upstream.

Interface Lower Than the Gravity-Current Depth

INTRUSIONS Suppose the interface between the fluids is allowed to diffuse. After a time the density distribution approaches that assumed in the theoretical work of Benjamin (1967) and Davis & Acrivos (1967) on waves in deep layers, later examined experimentally by Hurdis & Pao (1975) and Ono (1975). The collapse of mixed fluid can result in large-amplitude waves traveling in the thick interface for long distances without change of form. The waves have closed streamlines and consist mainly of mixed fluid from the collapsed region. Their formation and propagation has been described in detail recently by Kao & Pao (1980) and Maxworthy (1980). The Red Spot of Jupiter has been shown to have features in common with this type of solitary wave (Maxworthy et al. 1978).

BOUNDARY CURRENTS Maxworthy also described boundary gravity currents flowing in two-dimensional channels and radially with a thin dense miscible layer on the floor. Simpson (1980) has described similar two-dimensional experiments in which a gravity current was run at super- and subcritical speed compared with the solitary-wave speed. At supercritical speed the gravity current appeared almost unaffected by the stratification, but at subcritical speed a train of solitary waves in the thin layer moved ahead of the front. At an intermediate speed, when the density of the fluid in the current was roughly equal to that of the surroundings at the floor, a solitary wave with closed streamlines built up.

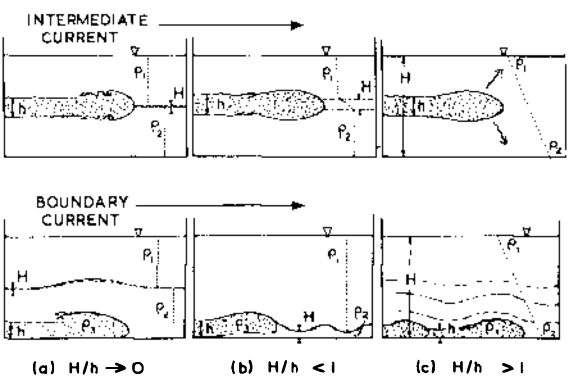

Figure 5 Gravity currents in stratified media and the formation of waves. The density of the intermediate currents is $(\rho_1 + \rho_2)/2$.

In the atmosphere, radar used in insect detection has outlined the presence of multiple frontal lines (Schaefer 1976). These are believed to have been formed by the advance of a gravity current through the strongly stratified nighttime boundary-layer inversion.

The propagation of sea-breeze fronts can be affected by waves in the developing nocturnal inversion. Extensive measurements of the progress of sea-breeze fronts in Australia by Clarke (1965) led him to suspect the formation late in the day of a vortex, cut off from the sea breeze, rolling on ahead of the main flow. The "cut-off vortex" described by Simpson, Mansfield & Milford (1977) seems consistent with laboratory observations of mixed fluid trapped within the leading solitary wave. Solitary waves measured by Christie et al. (1978), using pressure variations on the ground, were associated with sea-breeze fronts, and the "Morning Glory" phenomenon seen in Northern Australia seems to have features of both gravity currents and solitary waves (Clarke 1972, Neal et al. 1977). On the planet Mars a line of cloud resembling the Morning Glory has been seen at sunrise crossing the plain near Olympus Mons (Briggs et al. 1977, A. Pickersgill, unpublished).

Interface Thicker Than the Gravity-Current Depth

INTRUSIONS A continuous discharge of fluid into a linearly stratified fluid was studied by Masuda & Nagata (1974) and by Manins (1976). The intrusion velocities were very slow, and the heads of the intrusions were long and pointed. Forward-propagating disturbances and the ends of the tank played an important part in the flow.

Flows from a finite-volume mixed region into a linear stratification were described by Wu (1969). He found a strong internal-wave field generated by the collapse. Kao (1976) pointed out that the "principal stage" of the collapse described by Wu is a quasi-steady process—a gravity current in a stratified environment. The initial uniform-velocity regime observed in a gravity current released from a finite lock was negligible in Wu's experiments. However, Amen & Maxworthy (1980) observed an appreciable uniform regime in a flow into linear stratification.

A model for the evolution of such finite-volume mixed regions, or "turbulent spots," has been proposed by Barenblatt (1978). The waves radiated by these spots in their initial stages should interact between themselves and can also generate unstable shear flows which lead to the appearance of new turbulent spots of smaller scale. These, again in the initial stages of their collapse, radiate internal waves of small scale and so on in a cascade process. Barenblatt also obtained an expression for the radial spread of a spot in the long-lasting viscous regime, in which the distance r varies with $t^{1/8}$. Experimental confirmation of this work has been given by Zatsepin et al. (1978).

BOUNDARY CURRENTS Boundary currents, both above and beneath a uniformly stratified fluid, were examined experimentally by Simpson (1980). He showed how, for flows with an overall Froude number U_f/NH less than $1/\pi$ (where N is the buoyancy frequency), first-mode waves were formed which interacted with the head of the advancing gravity current to destroy the original front and to cause a succession of gravity-current heads (Figure 5*c*).

Consecutive fronts forming at the leading edge of a gravity current moving above stratified fluid suggest a possible explanation for a series of frontal lines seen occasionally as foam lines in fjords (McClimans 1978). Regular discontinuities in surface-temperature structure at power-station cooling-water flows (Adams & Carr 1975) and at a river flowing out to sea (Scarpace & Green 1973, Gross 1972) also may have this explanation.

UNIVERSALITY OF GRAVITY CURRENTS

Gravity currents have wide-ranging applications from avalanches and atmospheric pollution at one end of the alphabet to vulcanology and zoology at the other. Their effects have been detected on at least two other planets as well as on Earth. Research undertaken on one scientific discipline in this topic is being applied to previously unrelated disciplines. For example, work done on saline flows under lock-gates in canals has explained both the behavior of locust swarms and of plankton in the ocean. This trend will continue as further natural events are identified involving gravity-current processes.

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Literature Cited

Adams, B. A., Carr, J. F. 1975. Report of an aerial infra-red survey of cooling water plume movements at Pembroke Power Station. *C.E.G.B., S.W. Region Job No. ZB 1406*

Allen, J. R. L. 1971. Mixing at turbidity current heads, and its geological implications. *J. Sediment. Petrol.* 41:97–113

Amen, R., Maxworthy, T. 1980. The gravitational collapse of a mixed region into a linearly stratified fluid. *J. Fluid Mech.* 96:65–80

Barenblatt, G. I. 1978. Dynamics of turbulent spots and intrusions in a stably stratified fluid. *Izv. Atmos. Oceanic Phys.* 14:139–45

Barr, D. I. H. 1959. Some observations of small-scale thermal density currents. *Proc. 8th Congress IAHR, Montreal, Paper 6-C.* 22 pp.

Barr, D. I. H. 1967. Densimetric exchange flow in rectangular channels. III. Large scale experiments. *Houille Blanche* 6/1967:619–31

Bedard, A. J., Hooke, W. H., Beran, D. W. 1977. The Dulles Airport pressure jump detector array for gust front detection. *Bull. Am. Meteorol. Soc.* 58:920–26

Beghin, P., Hopfinger, E. J., Britter, R. E. 1981. Gravitational convection from instantaneous sources on inclined boundaries. *J. Fluid Mech.* 107:407–22

Benjamin, T. B. 1967. Internal waves of permanent form in fluids of great depth. *J. Fluid Mech.* 29:559–92

Benjamin, T. B. 1968. Gravity currents and related phenomena. *J. Fluid Mech.* 31:209–48
Briggs, G. A., Klaasen, K., Thorpe, T., Wellman, J., Baum, W. 1977. Martian dynamical phenomena during June–November 1976: Viking Orbiter results. *J. Geophys. Res.* 82:4121–50
Britter, R. E. 1979. The spread of a negatively buoyant plume in a calm environment. *Atmos. Environ.* 13:1241–47
Britter, R. E., Linden, P. F. 1980. The motion of the front of a gravity current traveling down an incline. *J. Fluid Mech.* 99:531–43
Britter, R. E., Simpson, J. E. 1978. Experiments on the dynamics of a gravity current head. *J. Fluid Mech.* 88:223–40
Chen, J-C., List, E. J. 1976. Spreading of buoyant discharges. *Proc. 1st CHMIT Seminar on Turbulent Buoyant Convection, Dubrovnik, 1976,* pp.171–82
Christie, D. R., Muirhead, K. J., Hales, A. L. 1978. On solitary waves in the atmosphere. *J. Atmos. Sci.* 35:805–25
Clarke, R. H. 1961. Mesostructure of dry cold fronts over featureless terrain. *J. Meteorol.* 18:715–35
Clarke, R. H. 1965. Horizontal mesoscale vortices in the atmosphere. *Aust. Meteorol. Mag.* No. 50:1–25
Clarke, R. H. 1972. The Morning Glory: an atmospheric hydraulic jump. *J. Appl. Meteorol.* 11:304–11
Clarke, R. H. 1973. A numerical model of the sea-breeze. *1st Aust. Conf. Heat and Mass Transfer, Monash,* pp. 41–48
Daly, B. J., Pracht, W. E. 1968. Numerical study of density current surges. *Phys. Fluids* 11:15–30
Davis, R. E., Acrivos, A. 1967. Solitary internal waves in deep water. *J. Fluid Mech.* 29:593–607
de Quervain, M. R. 1966. Problems of avalanche research. *1st Int. Symp. Sci. Aspects of Snow and Ice Avalanches, Davos, 1965,* pp. 15–22
Dzulynski, S. 1965. New data on experimental production of sedimentary structures. *J. Sediment. Petrol.* 35:196–212
Edwards, A., Edelsten, D. J. 1977. Deep water renewal of Loch Etive; a three basin Scottish Fjord. *Estuarine and Coastal Mar. Sci.* 5:575–95
England, W. G., Teuscher, L. H., Hauser, L. E., Freeman, B. E. 1978. Atmospheric dispersion of liquefied natural gas vapor clouds, using SIGMET. *Proc. 1978 Heat Transfer and Fluid Mech. Inst.* Stanford Univ. Press
Fay, J. A. 1969. The spread of oil slicks on a calm sea. In *Oil on the Sea,* ed. D. P. Hoult, pp. 53–63. New York: Plenum
Fay, J. A. 1980. Gravitational spread and dilution of heavy vapor clouds. *2nd IAHR Symp., Trondheim, June 1980,* pp. 471–94
Fujita, T. T., Byers, H. R. 1977. Spearhead echo and downburst in the crash of an airliner. *Mon. Weather Rev.* 105:129–46
Fujita, T. T., Caracena, F. 1977. An analysis of three weather-related accidents. *Bull. Am. Meteorol. Soc.* 58:1164–81
Garvine, R. W. 1974. Dynamics of small-scale oceanic fronts. *J. Phys. Oceanogr.* 4:557–69
Garvine, R. W., Monk, J. D. 1977. Frontal structure of a river plume. *J. Geophys. Res.* 79:2251–59
Georgeson, E. M. H. 1942. The free streaming of gases in sloping galleries. *Proc. R. Soc. London Ser. A* 180:484–93
Goff, R. C. 1976. Thunderstorm-outflow kinematics and dynamics. *NOAA Tech. Memo ERL NSSL-75.* 63 pp.
Gross, M. G. 1972. *Oceanography: A view of the Earth.* Englewood Cliffs, NJ: Prentice-Hall
Hall, F. F., Neff, W. D., Frazier, T. V. 1976. Wind shear observations in thunderstorm density currents. *Nature* 264:408–11
Holyer, J. Y., Huppert, H. E. 1980. Gravity currents entering a two-layer fluid. *J. Fluid Mech.* 100:739–67
Hopfinger, E. J., Tochon-Danguy, J. C. 1977. A model study of powder-snow avalanches. *Glaciology* 19:343–56
Hoult, D. P. 1972. Oil spreading on the sea. *Ann. Rev. Fluid Mech.* 4:341–68
Huppert, H. E., Simpson, J. E. 1980. The slumping of gravity currents. *J. Fluid Mech.* 99:785–99
Hurdis, D. A., Pao, H-P. 1975. Experimental observation of internal solitary waves in a stratified fluid. *Phys. Fluids* 18:385–86
Idso, S. B., Ingram, R. S., Pritchard, J. M. 1972. An American haboob. *Bull. Am. Meteorol. Soc.* 53:930–35
Jirka, G. H. 1980. Two-dimensional density current from continuous source in stratified crossflow *2nd Int. Symp. Stratified Flows, Trondheim, June 1980*
Kao, T. W. 1976. Principal stage of wake collapse in a stratified fluid: two-dimensional theory. *Phys. Fluids* 9:1071–74
Kao, T. W., Pao, H-P. 1980. Wake collapse in the thermocline and internal solitary waves. *J. Fluid Mech.* 97:115–27
Kao, T. W., Park, C., Pao, H-P. 1977. Buoyant surface discharge and small-scale oceanic fronts: a numerical study. *J. Geophys. Res.* 82:1747–52
Kao, T. W., Park, C., Pao, H-P. 1978. Inflows, density currents and fronts. *Phys. Fluids* 21:1912–22
Keulegan, G. H. 1957. An experimental study of the motion of saline water from locks into fresh water channels. *US Natl. Bur. Stand., Rep. 5168*

Koh, R. C. Y. 1971. Two-dimensional surface warm jets. *J. Hydraul. Div. ASCE* 97(HY6):819–36

Komar, P. D. 1972. Relative significance of head and body spill from a channelized turbidity current. *Geol. Soc. Am. Bull.* 83:1151–56

Komar, P. D. 1977. Computer simulation of turbidity current flow and the study of deep-sea channels and fan sedimentation. In *The Sea, Vol. 6 Marine Modeling*, pp. 603–21. Chichester, England: Wiley

Komar, P. D. 1979. Comparisons of the hydraulics of water flows in Martian outflow channels with flows of similar scale on Earth. *Icarus* 37:156–81

Kranenberg, C. 1978. Internal fronts in two-layer flow. *J. Hydraul. Div. ASCE* 104(HY10):1449–53

Lean, G. H., Whillock, A. Z. 1965. The behaviour of a warm water layer flowing over still water. *Proc. 11th Cong. IAHR, Leningrad, Vol. 2.* 12 pp.

Longinov, V. V. 1971. The problem of turbidity currents in the lithodynamics of the ocean. *Oceanology* 11:303–10

Lyons, W. A., Keen, C. S. 1976. Computed 24-hour trajectories for aerosols and gases in a lake/land breeze circulation cell on the western shore of Lake Michigan. *6th Conf. Weather Forecasting, Albany, NY*, pp. 78–83

Manins, P. C. 1976. Intrusion into a stratified fluid. *J. Fluid Mech.* 74:547–60

Masuda, A., Nagata, Y. 1974. Water wedge advancing along the interface between two homogeneous layers. *J. Oceanogr. Soc. Jpn.* 30:289–97

Maxworthy, T. 1980. On the formation of nonlinear internal waves from the gravitational collapse of mixed regions in two and three dimensions. *J. Fluid Mech.* 96:47–64

Maxworthy, T., Redekopp, L. G., Weidman, P. 1978. On the production of planetary solitary waves: applications to the Jovian atmosphere. *Icarus* 33:338–409

McClimans, T. A. 1978. Fronts in fjords. *Geophys. Astrophys. Fluid Dyn.* 11:23–34

McQuaid, J. 1979. Dispersion of heavier-than-air gases in the atmosphere. *Health and Safety Executive Tech Paper No. 8.* 16 pp.

Middleton, G. V. 1966. Experiments on density and turbidity currents. I, Motion of the head. *Can. J. Earth Sci.* 3:523–46

Miller, M. J., Betts, A. K. 1977. Travelling convective storms over Venezuela. *Mon. Weather Rev.* 105:833–48

Moore, J. G. 1967. Base surge in recent volcanic eruptions. *Bull. Volcanol.* 30:337–63

Moore, J. G., Melson, W. G. 1969. Nuées ardentes of the 1968 eruption of Mayon volcano, Philippines. *Bull. Volcanol.* 33:600–20

Neal, A. B., Butterworth, I. J., Murphy, K. M. 1977. The Morning Glory. *Weather* 32:176–83

O'Brien, M. P., Cherno, J. 1934. Model law for motion of salt water through fresh. *Trans. Am. Soc. Civil Engrs.* 99:576–94

Officer, C. B. 1976. *Physical Oceanography of Estuaries and Associated Coastal Waters.* NY: Wiley

Ono, H. 1975. Algebraic solitary waves in stratified fluids. *J. Phys. Soc. Jpn.* 39:1082–91

Pingree, R. D., Forster, G. R., Morrison, G. K. 1974. Turbulent convergent tidal fronts. *J. Mar. Biol. Assoc. U.K.* 54:469–79

Prandtl, L. 1952. *Fluid Dynamics.* London: Blackie

Pykhov, N. V. 1973. The movements of sediments over an inclined sea floor after disturbance of their stability. *Oceanology* 13:893–96

Pykhov, N. V., Longinov, V. V. 1972. On the methods of computing the parameters of turbidity currents. *Oceanology* 12:761–71

Rainey, R. C. 1963. Meteorology and the migration of desert locusts. *WMO No. 138 TP. 64. Tech. Notes No. 54.* 115 pp.

Reimers, C. E., Komar, P. D. 1979. Evidence for explosive volcanic density currents on certain Martian volcanoes. *Icarus* 39:88–110

Riddell, J. C. 1970. Arrested saline wedge. *Houille Blanche* 4/1970:317–30

Scarpace, F. L., Green, T. 1973. Dynamic surface temperature structure of thermal plumes. *Water Resources Res.* 9:138–53

Schaefer, G. W. 1976. Radar observations of insect flight. In *Insect Flight: Symp. R. Entomol. Soc. London No. 7*, pp. 157–97

Schaefer, G. W. 1979. An airborne radar technique for the investigation and control of migrating pest insects. *Philos. Trans. R. Soc. London Ser. B* 287:459–65

Schmidt, W. 1911. Zur Mechanik der Böen. *Z. Meteorol.* 28:355–62

Shen, H. W., Roper, A. T. 1970. Dynamics of snow avalanche. *Bull. Int. Assoc. Sci. Hydrology* 15:7–26

Simpson, J. E. 1969. A comparison between laboratory and atmospheric density currents. *Q. J. R. Meteorol. Soc.* 95:758–65

Simpson, J. E. 1972a. Effects of the lower boundary on the head of a gravity current. *J. Fluid Mech.* 53:759–68

Simpson, J. E. 1972b. Instability patterns at the head of a cold outflow. *Proc. 1st Int. Symp. Tech. & Sci. Motorless Flight, MIT, Cambridge, Mass.*, pp. 8–18

Simpson, J. E. 1980. Experiments on gravity currents in stratified fluids. *Geophys. J. R. Astron. Soc.* 61:225 (Abstract only)

Simpson, J. E., Britter, R. E. 1979a. The dynamics of the head of a gravity current advancing over a horizontal surface. *J. Fluid Mech.* 94:477–95

Simpson, J. E., Britter, R. E. 1979b. The form of the head of an intrusive gravity current. *Geophys. J. R. Astron. Soc.* 57:289 (Abstract only)

Simpson, J. E., Britter, R. E. 1980. A laboratory model of an atmospheric mesofront. *Q. J. R. Meteorol. Soc.* 106:485–500

Simpson, J. E. Mansfield, D. A., Milford, J. R. 1977. Inland penetration of sea-breeze fronts. *Q. J. R. Meteorol. Soc.* 103:46–76

Simpson, J. H., Allen, C. M., Morris, N. C. G. 1978. Fronts on the continental shelf. *J. Geophys. Res.* 83:4607–14

Stith, J. L., Hobbs, P. V., Radke, L. F. 1977. Observations of a nuée ardente from the St. Augustine volcano. *Geophys. Res. Lett.* 4:259–62

Thorpe, A. J., Miller, M. J., Moncrieff, M. W. 1980. Dynamical models of two-dimensional downdraughts. *Q. J. R. Meteorol. Soc.* 106:463–84

Thorpe, S. A. 1973. Experiments on instability and turbulence in a stratified shear flow. *J. Fluid Mech.* 61:731–51

Turner, J. S. 1968. The influence of molecular diffusivity on turbulent entrainment across a density interface. *J. Fluid Mech.* 33:639–56

Uda, M. 1938. Researches on 'Siome' or current rip in the seas and oceans. *Geophys. Mag.* 11:307–72

van Ulden, A. P. 1974. On the spreading of a heavy gas released near the ground. *1st Int. Loss Prevention Symp., The Hague, May 1974,* pp. 221–26

Vasiliev, O. F., Kvon, V. I., Chernyshova, R. T. 1973. Mathematical modelling of the thermal pollution of a water body. *IAHR Cong., Istanbul, 1973, Pap. B17.*

Voellmy, A. 1955. Uber die Zerstörungskraft von Lawinen. *Schweiz. Bauzeitung* 73:159–65, 212–17

von Kármán, T. 1940. The engineer grapples with non-linear problems. *Bull. Am. Math. Soc.* 46:615–83

Vreugdenhil, C. B. 1976. Mathematical investigation of stratified flow. In *Rijkswaterstaat Communications No. 26, DHL, The Hague*, pp. 87–114

Wilkinson, D. L., Wood, I. R. 1971. A rapidly varying flow phenomenon in a two-layer flow. *J. Fluid Mech.* 47:241–56

Wilkinson, D. L., Wood, I. R. 1972. Some observations on the motion of the head of a density current. *J. Hydraul. Res.* 10:305–24

Wilson, C. J. N. 1980. The role of fluidization in the emplacement of pyroclastic flow: An experimental approach. *J. Volcanol. and Geothermal Res.* 8:231–49

Winant, C. D., Bratkovich, A. 1977. Structure and mixing within the frontal region of a density current. *6th Aust. Hydraul. & Fluid Mech. Conf., Adelaide, Australia, Dec. 1977,* pp. 9–12

Wood, I. R. 1965. Studies in unsteady self preserving turbulent flows. *Univ. N. S. Wales, Manly Vale; Australia, Rep. No. 81.* 152 pp.

Wood, I. R. 1967. Horizontal two-dimensional density current. *J. Hydraul. Div. ASCE* 93(HY2):35–42

Wu, J. 1969. Mixed region collapse with internal wave generation in a density-stratified medium. *J. Fluid Mech.* 35:531–44

Yih, C-S. 1980. *Stratified flows,* pp. 204–7. New York: Academic

Zatsepin, A. G., Fedorov, K. N., Voropayev, S. I., Pavlov, A. M. 1978. Experimental study of the spreading of a mixed region in a stratified fluid. *Izv. Atmos. and Oceanic Phys.* 14:170–3