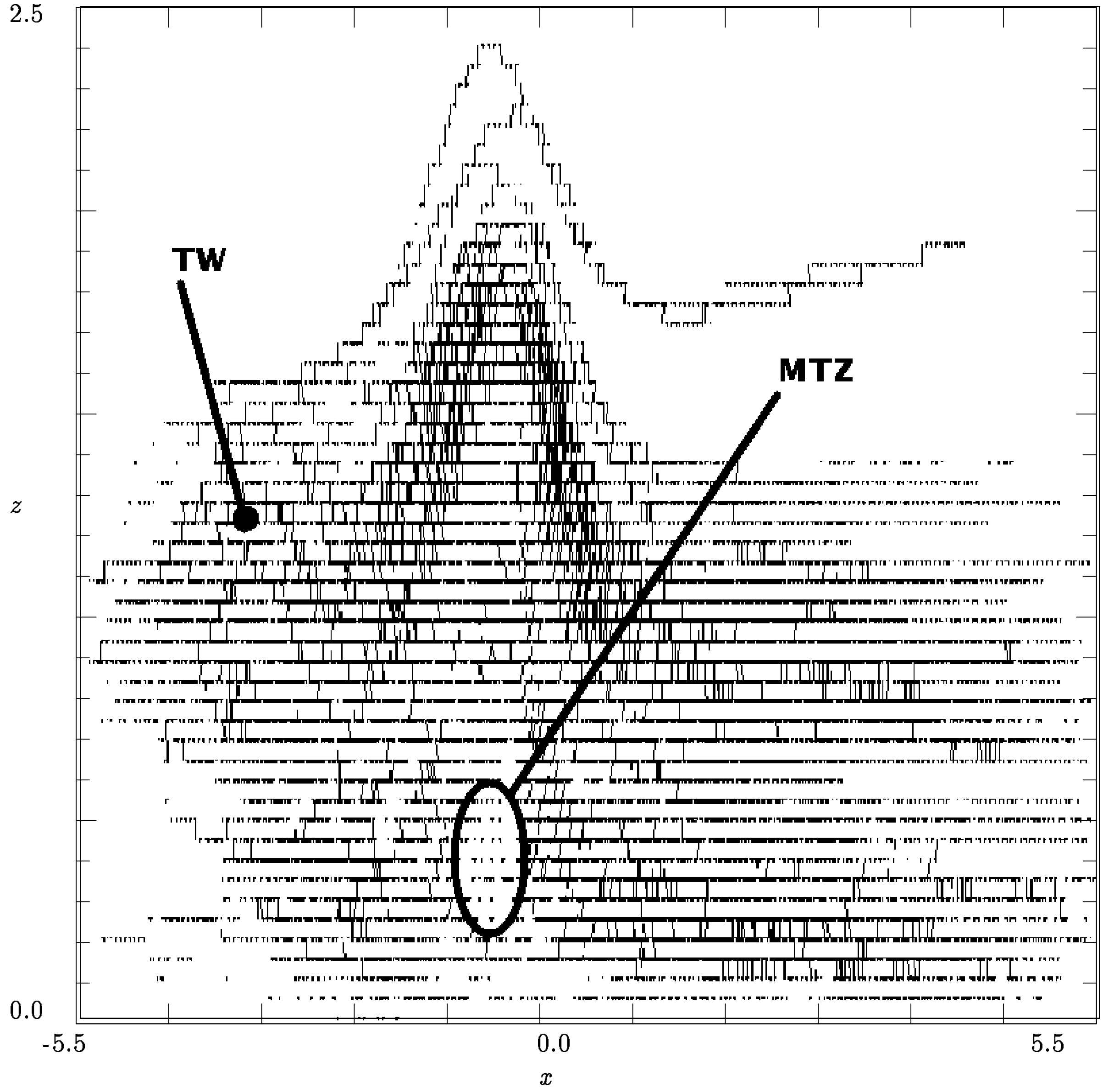

Figure 9: Pathline pattern of an IPF. The data are identical to that of figure 8, but plotted in a frame of reference moving with the IPF at its speed of propagation, 1.63 ± 0.4 cm s^{-1}. The pathlines are interpreted as approximate streamlines. The particles were tracked for a greater time before the passage of the IPF than after; hence the relative displacement of the zero on the x-axis and the peak in the pattern. MTZ: the mass-transporting zone, in which particles appear quasi-stationary in this frame of reference; TW: a small trailing wave. Other details as figure 8.

tracks (approximate streamlines) are shown in figure 10. The upper tracks illustrate the wave-like character of the upper wave-activity zone, including the trailing wave. The lower tracks simply stagnate at the boundary of the mass-transport zone. No evidence of recirculating flow can be discerned, however, this point will be discussed in §5 below.

5 Discussion

Existing theory and numerical work on strongly nonlinear waves (Tung et al 1982; Brown & Christie 1994) predicts wave speed rising with amplitude faster than weakly nonlinear theory. Experiments by Stamp & Jacka (1995) agreed with these predictions. The present experiments are unable to confirm this trend, partly because of the comparatively narrow amplitude range studied, and possibly because the IPFs are sufficiently density-driven to make wave-dynamical analyses inappropriate.

The dye and particle-tracking experiments show that transport of mass occurs over a distance an order of magnitude greater than the horizontal 'wavelength' of the IPF, placing it well beyond the behaviour permitted to linear or weakly nonlinear waves. This is consistent with amplitudes being generally larger than the acceptable range of validity of weakly nonlinear theory. Equally, the lack of a continuous upstream supply of dense fluid forcing the motion makes it impossible to describe the IPF as a gravity current, and the fact that fluid is lost to the trail implies that the feeder-flow structure characteristic of gravity currents (Simpson 1987) does not exist. While in many cases propagation speeds are greater than linear wave theory would predict, the IPFs studied here do not all travel faster than the linear speed, as solitary waves are expected to. (See figure 4.)

The formation of a closed streamline zone has been predicted by the numerical studies of Davis & Acrivos (1967) and by Tung et al

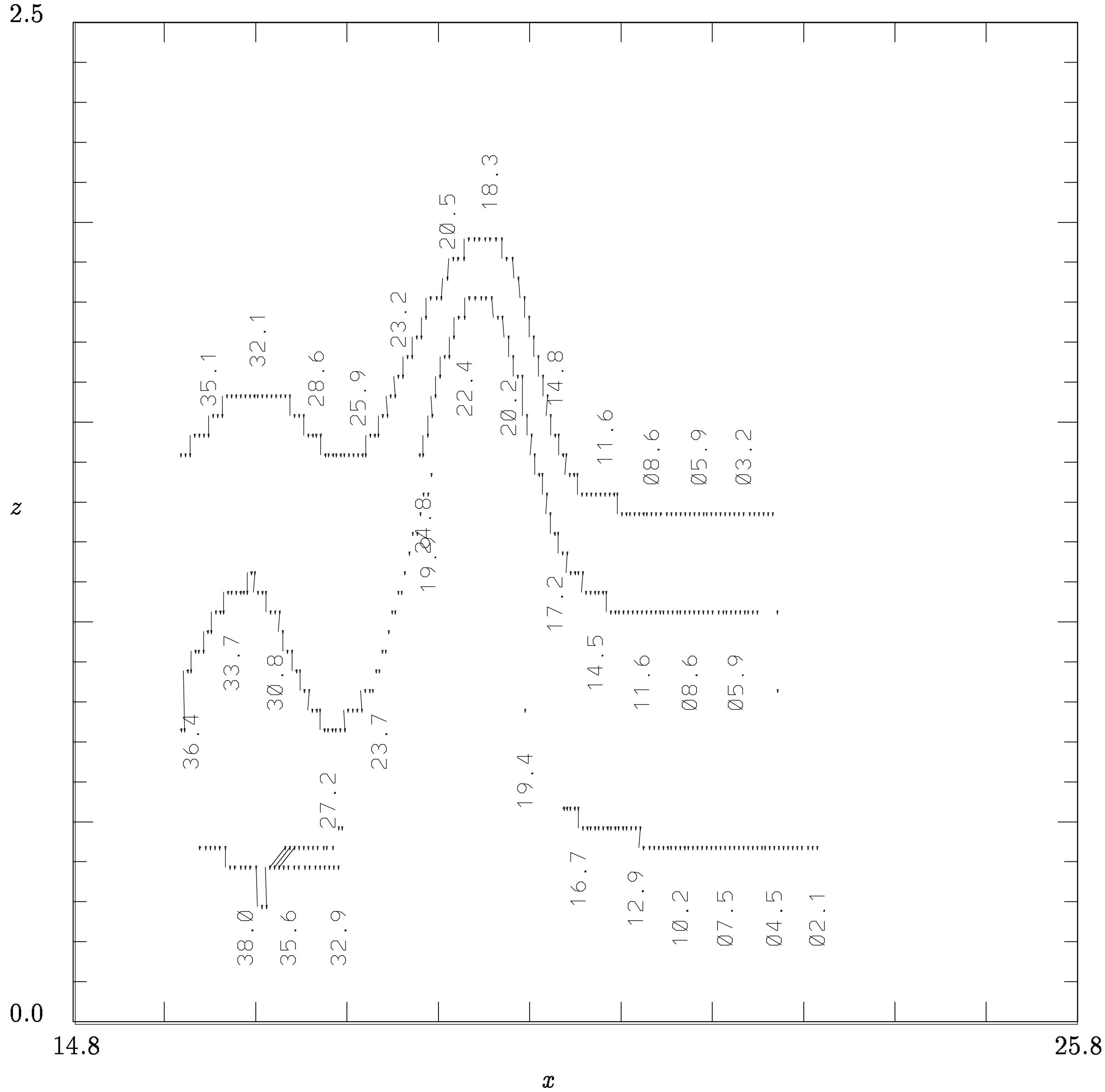

Figure 10: Pathline pattern of an IPF, in a frame of reference moving with the IPF at its speed of propagation, 1.63 ± 0.4 cm s^{-1}. As figure 9, here only selected particle tracks are shown. Time elapsed since thermal release is non-dimensionalized using the buoyancy frequency $N = 1.35$ s^{-1}. Time labels shown appear directly above or below the particle's location at that time. The bottom track stagnates at the boundary of the mass-transport zone.

(1982) and has been associated with the mass-transporting zone observed in experiments. If the streamfunction is continuous across a closed streamline, it implies a net circulation or at least some vorticity within. However, relative motion within the mass-transporting zone was not found in the present experiments. This should not be too surprising, in hindsight, for the above-mentioned authors note that the theoretical basis of their calculations is invalidated once closed streamlines form.

The presence of a solid boundary can change the flow structure of the present system significantly from the interfacial soliton system; Stamp & Jacka (1995) studied an interfacial soliton system and did report circulation within "cells", although, since fluid was continually entrained into these cells and lost from them, they were not consistent with the closed-streamline regions predicted numerically by Davis & Acrivos (1967) and Tung et al (1982).

It is possible that the absence of significant vorticity within the mass-transporting zone may be related to bottom friction – the boundary layer completely damping out the flow pattern that would be calculated under inviscid theory. Such calculations (Tung et al 1982) were made for solitons on an interfacial layer, not at a boundary as in the present experiments. For an inviscid flow, they should be equally applicable, since the centre streamline could be replaced by a solid boundary. However, on a solid boundary there will be a viscous boundary layer. According to §4.1, turbulent motions were no longer evident by the time the IPF is formed. Thus, the influence of a turbulent boundary layer is hard to gauge, and moreover, there is no evidence of significant turbulent damping once the IPF is formed. A purely viscous (rather than turbulently eddy-viscous) boundary layer would be too small to affect flow in the closed-streamline zone. This is because, given flow speeds relative to the boundary of the order of 1 cm s^{-1}, the length scales of the viscous boundary layer would be of order tenths of a mm, compared with a closed-streamline zone that is about 1 cm in size.

One possibility is that the vorticity generated at the boundary by the initial thermal rotation is advected with the transported mass. Being of opposite sign to the rotation expected within a strongly non-linear soliton, the advected vorticity effectively cancels it. It may be possible that an intermediate spatial zone exists, separating the lower mass-transport zone from the upper wave-dynamics zone, and that there is a net rotation of fluid in this intermediate zone. The regions which can definitely be called a wave-activity zone and definitely a mass-transport zone in figure 8 or figure 9 are not quite adjacent. This may be due to the lack of clarity in the experimental data, but it may also be due to the presence of an intermediate zone in which flow is rotating. This zone would allow a smooth matching of the vorticity gradient in the wave-dynamics zone to an apparently zero vorticity in the mass-transport zone.

The reduction with time in the amplitude of the IPF is small, compared to the reduction in the size of the encapsulated thermal mass which leaks out in the trail. This may be because fluid from the stratified layer has been entrained to replace some of the lost thermal mass; alternatively, kinetic energy may have been transferred from the lost thermal mass to the wave-action zone. Christie (1989) has studied numerically the evolution of a train of solitary waves. He noted that the amplitude of the leading soliton may become exceptionally large as the evolution from initial disturbance to final state progresses. This tendency for amplitude growth may partly offset the reduction owing to loss of thermal mass. A small trailing wave was noted in the present experiments, so the main IPF could be considered part of a train.

The existence of the small trailing wave behind many of the IPFs may be consistent with the theory described by Akylas & Grimshaw (1992). In their theory, oscillatory 'tails' represent a drain of energy from the main soliton. Their theory is specific to waves on a thin interface in a deep fluid, but may apply to an interfacial region in the present experiments. The loss of fluid to the thin trail behind the IPF represents a loss of momentum.

6 Conclusion

The impact of a descending two-dimensional thermal on a thin stratified layer overlying a solid surface leads to the formation of horizontally propagating fluid masses on the surface. In this system, there is a pair of such masses, created from each half of the thermal vortex. Each of these masses encapsulates fluid from the thermal. They travel along with solitary displacements in the isopycnals of the background stratification.

These phenomena could be called 'isolated propagating flows' (IPFs). They are found for $N^2H^3/Q_0 < 50$ to 80. The IPF occurs as a density-driven flow evolves with time into a wave-dominated flow. They lack the continuous upstream supply of dense fluid and the feeder-flow internal structure characteristic of gravity currents. They transport substantial mass over a distance an order of magnitude greater than their horizontal 'wavelength'. Hence, from the viewpoint of wave mechanics, they must be regarded as a type of strongly nonlinear solitary wave. They are of importance in understanding environmental phenomena such as wind shear due to thunderstorm outflows. They are also relevant to the generation of 'solitary' waves under leads in the winter polar ice, which may appear like outward 'jet-like' flows.

The IPF initially transports substantial mass of thermal fluid. Some leakage of this fluid always occurs, ultimately leading to a loss of the original mass of thermal fluid. The propagation speed of IPFs (averaged over $x = 0$ to $x = 40$) followed a plausible scaling for a density-driven flow, described by

$$\frac{c}{(Q_0/H)^{1/2}} = f\left(\frac{N^2H^3}{Q_0}\right), \qquad (8)$$

for $N^2H^3/Q_0 <$ 50 to 80, which is independent of the second parameter H/L. Note that a wave-dominated scaling would incorporate the effect of L. However, at large N^2H^3/Q_0, this scaling based on density-driven effects breaks down. This is consistent with visual observations of those datapoints representing waves of small or negligible amplitude, rather than an IPF.

The amplitudes observed were generally beyond the range of validity of weakly nonlinear theory. IPF speeds were both above and below to the first-vertical-mode linear wave speed; most were significantly greater, but some IPFs also travelled slower than the linear speed.

The vertical structure of the observed IPFs consists of an upper zone in which the behaviour is essentially wave-dynamical, and a lower zone in which transport of mass occurs. The mass-transporting zone slowly shrinks until no significant mass transport occurs. After this stage the flow behaves essentially as a weakly nonlinear solitary wave.

The absence of significant vorticity within the mass-transporting zone, and its presence in the wave-dynamical zone, implies that a single mathematical solution may not be possible throughout the IPF. Separate analyses may be required, to be matched at the boundary between the zones. An inviscid solution for the wave-dynamical zone, matched to an interior, possibly eddy-viscous, solution may capture most of the relevant dynamics.

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List of Figures