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A bi-modal structure imposed on gravity driven boundary currents in rotating systems by effects of the bottom topography

P. J. Thomas, P. F. Linden

Abstract An experimental observation related to the influence of the bottom topography on the development of gravity driven surface boundary currents in rotating systems is described and discussed. The results presented concern the local flow geometry in the vicinity of the head of the current. It is observed that, depending on the values of the independent experimental variables and the inclination angle of the bottom topography, the current propagates along the boundary with its head being either attached to or detached from the coastline. An appropriate scaling of the experimental data reveals that the attached and detached head mode occur in two distinct parameter regimes which are separated from each other by a well defined border. The discussion of the results suggests that this border identifies the division between two flow regimes in which the local flow structure in the vicinity of the head of the gravity current is and where it is not significantly influenced by the bottom topography.

1 Introduction

The purpose of this paper is to document and discuss an experimental observation concerning the influence of the bottom topography on the propagation and development of gravity driven boundary currents in a rotating system. Our laboratory study aims at simulating the fluid dynamics of coastal currents developing as a result of buoyant, estuarine fresh water discharges into an environment of dense, salty ocean water. As is well known such discharges can lead to surface currents flowing along the coast. The currents are restricted to the coastal region by the action of the Coriolis force arising in association with the rotation of the earth. The action of the Coriolis force results in currents which propagate keeping the coast to their right in the northern hemisphere and to their left in the southern hemisphere (Griffiths and Linden 1981).

Some typical examples of natural gravity currents large enough to be affected by the rotation of the earth are for instance the estuarine fresh water discharges of rivers such as the Amazon in Brazil or the Humber in England. Further examples are discharges from fjords or the East Greenland Current which carries cold, fresh polar water southward from the Arctic Ocean along the east coast of Greenland. Because of its importance with regard to environmental issues it is essential to gain a detailed knowledge of the fluid dynamics of coastal currents. The estuarine-coastal zone interaction is of major importance in determining the coupling of the eco-system of the land and the ocean. The presence and the interaction of coastal currents in the coastal region is one major contribution to this coupling.

Gravity currents occurring in various flows in the environment have in the past been the scope of numerous studies. Detailed accounts of the relevant literature can be found in Simpson's (1997) well known book or in the review articles by Simpson (1982) or Griffiths (1986). Here we report on an experimental observation which has apparently not been described previously in the existing literature. The observation concerns a feature associated with gravity currents propagating under the influence of background rotation along boundaries over an inclined bottom topography.

2 Experimental set-up

We have carried out experiments in a circular perspex tank (radius $R = 44.75$ cm) positioned on a computer controlled rotating turntable (see Fig. 1). By using suitable insets for the tank it was possible to study currents propagating along boundaries over bottom topographies with various inclination angles α_0 to the horizontal between $\alpha_0 = 15^\circ$ and $\alpha_0 = 90^\circ$. The tank was filled with salt water of density ρ_2 representing the ocean. For currents propagating along a vertical wall ($\alpha_0 = 90^\circ$) the fluid depth was approximately 15 cm. This depth was found to be sufficient to ensure that the fluid depth had no observable effect on the form of propagation and can be considered as infinite. For currents propagating over sloping bottoms ($\alpha_0 < 90^\circ$), the depth was between approximately 15 cm and

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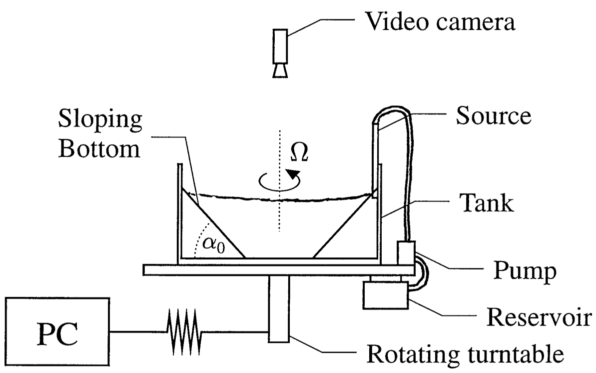

Fig. 1. Sketch of the experimental set-up

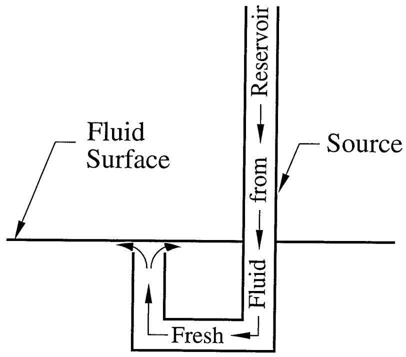

Fig. 3. Sketch of cross-section of flow geometry near the source illustrating the direction of the fluid discharge

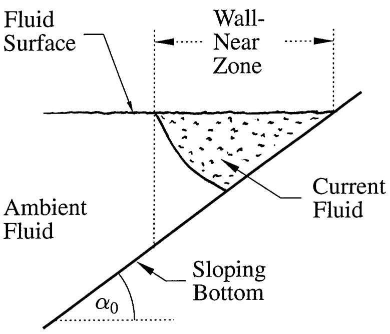

Fig. 2. Sketch of cross-section of local flow geometry in wall-near zone in the case of currents propagating along an inclined boundary

25 cm and was chosen according to the inset's exact geometry imposed by the angle α_0. With regard to the cross-sectional flow geometry illustrated in Fig. 2 it is evident, however, that the exact filling height is of no relevance to the propagation of the current when sloping walls are considered. In this case the flow is governed by the local cross-sectional geometry in a wall-near zone with a width corresponding to the width of the current. After filling the tank the turntable was spun at a constant rotation rate Ω and the fluid in the tank was allowed to reach solid body rotation. Boundary currents were then generated by releasing buoyant, fresh water with a density ρ_1 from a small source attached to the inset in the tank. The source consisted of a circular tube with an inner diameter of 8 mm and the end of the tube was adjusted to coincide with the level of the surface of the salt water in the tank (Fig. 3). Fresh, buoyant fluid was supplied to the source from a reservoir mounted on the turntable by means of a calibrated peristaltic pump (Watson-Marlow 505*U*/*RL*). The fresh fluid was discharged vertically upwards rather than parallel to the surface of the dense salt water in the tank as would be the case for estuarine discharges in oceanographic surroundings. This direction of fluid discharge was chosen in order to minimise influences due to momentum flux and, in particular also, in order to minimise mixing of discharged fluid with ambient fluid in the region of the source.

The experiments were carried out for rotation rates in the range of $0.5\ \mathrm{rad\,s^{-1}} \leqslant \Omega \leqslant 2.5\ \mathrm{rad\,s^{-1}}$. The volume flux q_0 of discharged, fresh fluid was in the range of $9.44\ \mathrm{cm^3\,s^{-1}} \leqslant q_0 \leqslant 23.2\ \mathrm{cm^3\,s^{-1}}$. The reduced gravitational acceleration g', which characterises the buoyancy forces, is defined as

$$g' = g\frac{\rho_2 - \rho_1}{\rho_2} \tag{1}$$

(g: gravitational acceleration) and it was varied in the range of $6.8\ \mathrm{cm\,s^{-2}} < g' < 33\ \mathrm{cm\,s^{-2}}$. A dimensional analysis of the flow problem under consideration shows that an appropriate dimensionless parameter characterising each experiment can be defined as

$$\Pi = \frac{q_0^{1/5}\Omega}{g'^{3/5}} \tag{2}$$

The flow was visualised by adding some food colouring to the fresh water in the reservoir. During each experiment the boundary current was filmed with a video camera which was rigidly mounted on the rotating turntable.

3
Experimental results

The photograph in Fig. 4 shows an example of one of the currents studied. The displayed photograph shows a current propagating along a vertical wall at $t \approx 60$ s after the commencing of the discharge of fresh fluid from the source. In Fig. 4 the sense of rotation of the turntable is anti-clockwise. The current flows along the wall of the tank in a cyclonic sense, i.e. also in the anti-clockwise direction keeping the boundary to its right. The current head propagates around the entire circumference of the circular tank until it eventually returns to the location of the source when the experiment is being terminated.

The experimental observation which is the scope of this report concerns the local geometry of the flow field in the region of the current head. It was observed that the flow geometry in this region displayed for each experiment one of two different modes. These two modes are illustrated by the flow visualization pictures of Fig. 5a, b. Depending on the values of the independent experimental variables and the inclination angle α_0 of the bottom the current head was observed to be either attached (Fig. 5a) to the wall of the tank or detached (Fig. 5b) from it. For 4 experiments, out

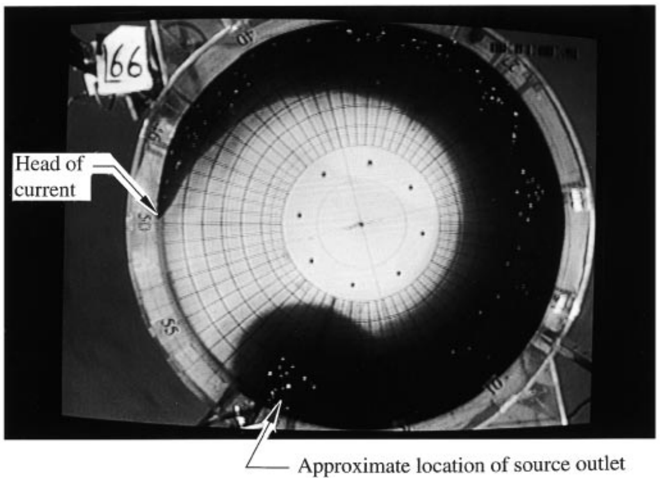

Fig. 4. Flow visualization taken from a video recording of an experiment with $\Omega = 0.5$ rad s^{-1}, $g' = 86.3$ cm s^{-2} and $q_0 = 20$ cm^3 s^{-1} ($\Pi = 0.063$) at $t \approx 60$ s. The current flows along a vertical wall. The sense of the rotation of the turntable is anti-clockwise. The current also propagates anti-clockwise such that it moves along the wall of the tank keeping the wall (coast) to its right

of a total of 65, it was observed that a current displaying two heads, i.e. an attached head and simultaneously a detached head, as illustrated in Fig. 5c, was formed. Whenever such an ambiguous experiment was repeated a current with an unequivocal head structure was observed.

It is emphasised that the detachment of the current head described here appears to be a different phenomenon than the type of detachment of boundary currents which is for instance discussed by Spitz and Nof (1991), Verron and Blayo (1996), Baines and Hughes (1996) or related research. In the present case the currents appear only locally detached from the wall, i.e. they propagate along the coast with only the region in the immediate vicinity of their head being separated from it. The currents discussed in the papers cited above do, however, separate from the coast as a whole at a certain point and they then propagate away from the coast downstream of the separation point.

Figure 6 summarises the numeric value of the dimensionless parameter Π for each experiment as a function of the associated inclination angle α_0 of the wall. The different types of markers identify currents with an attached head (squares), a detached head (circles), or a double-head structure (crosses). Figure 6 displays the main experimental result of this report. The figure shows that attached and detached current heads occur in two distinct regions of the $\Pi - \alpha_0$ plane separated by a relatively well-defined border. The approximate location of the border is indicated in the figure for $15^\circ \lesssim \alpha_0 \lesssim 75^\circ$ by the dotted line given by $\alpha_0 = 55 \cdot \Pi$. For runs with experimental conditions in the separated zone the separation was the stronger the further away the experimental conditions were from the border between the two regions.

For the experiments carried out along a vertical wall the current head remained attached in all cases. The data points for the 4 ambiguous experiments for which a double-head structure was observed are located in the immediate proximity of the border between the two regions. In the coastal ocean the

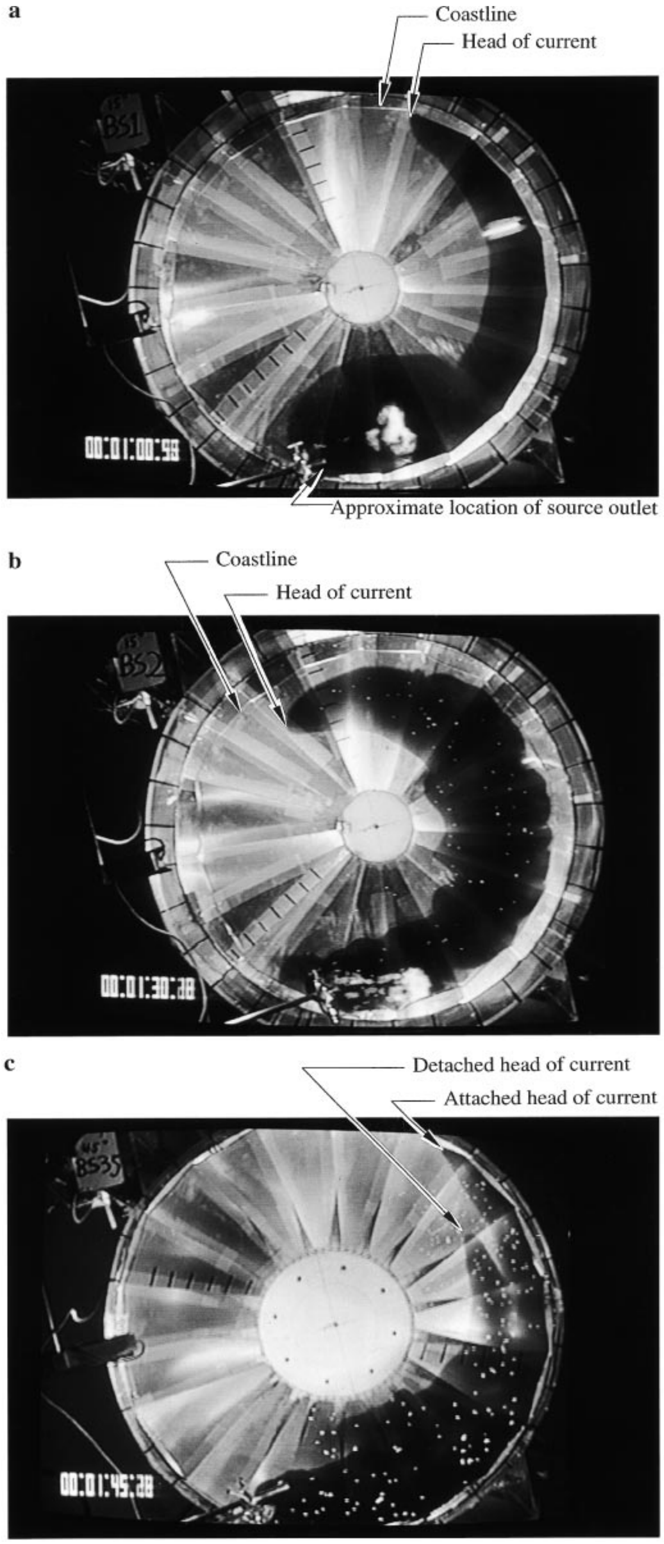

Fig. 5. Flow visualisations illustrating the geometry of the diffrerent modes observed for the structure of the current head. **a** attached head ($\Pi = 0.163$, $\alpha_0 = 15^\circ$), **b** detached head ($\Pi = 0.486$, $\alpha_0 = 15^\circ$), **c** doulbe head structure ($\Pi = 0.809$, $\alpha_0 = 45^\circ$)

value of Π would typically be of the order of 10^{-4} or less. These values are much smaller than those we were able to produce in the laboratory. However, if the results of the simple scaling of Fig. 6 could indeed be extrapolated to the coastal ocean then it

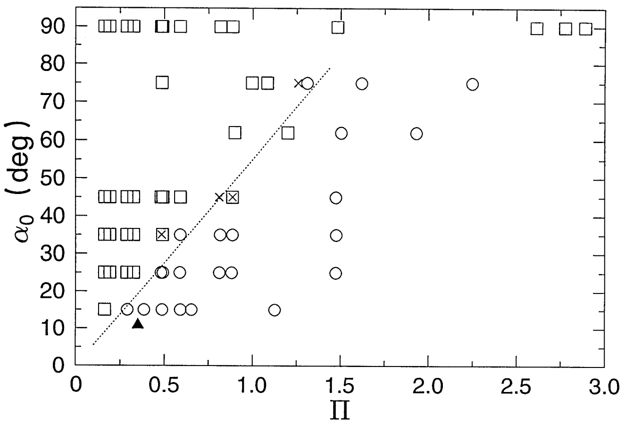

Fig. 6. Experimental data points showing for which inclination angles α_0 attached heads (□), detached heads (○), and double heads (×), were observed for different numeric values of the non-dimensional parameter Π, ▲: data point obtained from Whitehead and Chapman (1986), ... $\alpha_0 = 55 \cdot \Pi$

would follow that for realistic smallest values of α_0 of the order of 1° only attached current heads should be observed in such surroundings.

Although the separation of the current head discussed by us in this paper has not been described before there is, however, a picture available in the literature which does in fact display this feature – see Fig. 3 of Whitehead and Chapman (1986). From their data we estimate a value of $\Pi \approx 0.35$ for the current displayed in their figure. The false bottom in their study has a slope of 1 : 5 corresponding to an inclination angle of $\alpha_0 \approx 11.3^\circ$. A comparison with our Fig. 6 shows that the experimental conditions for their current were located in the region of the detached head mode and relatively close to the border between the two regions. From our results a slightly detached head would thus be expected in agreement with Whitehead and Chapman's Fig. 3.

4 Conclusion

We have described and discussed an experimental observation related to the influence of the bottom topography on the development of gravity driven surface boundary currents in rotating systems. The particular feature of the currents studied in this report has apparently not been described in the existing literature and concerns the flow geometry in the vicinity of the head of the gravity currents. Depending on the values of the independent experimental variables and the inclination angle of the bottom topograhy the current head was observed to be either attached to or detached from the boundary along which it propagates. Based on an appropriate scaling of the experimental data the main conclusion of this investigation is that the experimental data appear to suggest the existence of two different current modes for currents which are subject to the flow conditions considered here. If the scaling of the laboratory data can be extrapolated to oceanographic conditions then it appears likely that only the attached current head mode should be observed in the coastal ocean.

Some of our as yet unpublished experiments involved with currents propagating along vertical walls have shown that the depth of the currents at the wall of the tank decreases approximately linearly from the source to its head over a large interval extending over up to 80% of the total current length. These experiments have also shown that the current depth increases with an increasing rotation rate Ω, an increasing flow rate q_0 and also with a decreasing reduced gravitational acceleration g'. Hence, the larger the numeric value of Π the larger the current depth. On the basis of this qualitative result obtained for vertical walls one can thus conclude for the inclined wall case that the current head should be influenced by the presence of the sloping bottom the stronger the larger the numeric value of Π. This result is in qualitative agreement with the results displayed in Fig. 6 which show that for increasing values of Π an increasingly steep bottom, and accordingly an increasing fluid depth, is required in order to be able to observe the attached head structure for a particular current. On the basis of this it would thus appear that the border in the $\Pi - \alpha_0$ plane which separates the two regions where the attached and the detached head modes occur identifies for which value of Π the bottom topography becomes of significant importance in the immediate vicinity of the current's head for a particular inclination angle α_0 of the bottom. However, this does of course not imply that the overall current development is independent of the bottom topography whenever the head remains attached to the wall.

During the research which has led to the results presented in this paper we have made various different attempts to derive a theoretical model for the observed separation of the current head in terms of the principle of conservation of potential vorticity. Nevertheless, we have so far not succeeded in producing a satisfactory explanation for the experimental results. In order to develop a theoretical model it would be helpful to have some quantitative information relating to the cross-sectional structure of the flow velocity within the current; this information is, however, presently not available to us.

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